Renewable and Sustainable Energy Reviews 82 (2018) 215–231

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Alternative pathways for efficient CO_2 capture by hybrid processes—A review

Chunfeng Song[a,b,*], Qingling Liu[a], Na Ji[a], Shuai Deng[b], Jun Zhao[b], Yang Li[c], Yingjin Song[a], Hailong Li[d]

[a] Tianjin Key Laboratory of Indoor Air Environmental Quality Control, School of Environmental Science and Technology, Tianjin University, 135 Yaguan Road, Haihe Education Park, Tianjin, China
[b] Key Laboratory of Efficient Utilization of Low and Medium Grade Energy (Tianjin University), Ministry of Education, Tianjin
[c] Tianjin Institute of Industrial Biotechnology, Chinese Academy of Sciences, Tianjin, 300308, China
[d] Mälardalen University, School of Sustainable Development of Society and Technology, SE-721 23 Västerås, Sweden

ARTICLE INFO

Keywords:
CCS
Hybrid CO_2 capture
Absorption
Adsorption
Membrane
Cryogenic

ABSTRACT

CO_2 capture and storage technologies have been recognized as the primary option to mitigate the issue of climate change caused by the utilization of fossil fuels. In the last decades, several CO_2 capture approaches have been developed, such as absorption, adsorption, membrane, cryogenic, hydrate and chemical looping combustion etc. However, the energy penalty is a general challenge for each technology. To overcome the disadvantages of standalone technology, the combination of two or more approaches (namely hybrid CO_2 capture processes) has been considered as a potential option. In this work, the status and development of hybrid CO_2 capture processes is presented in a classification of primary technology as absorption-based, adsorption-based, membrane-based and cryogenic-based. The detail configuration of each hybrid process is introduced. Simultaneously, the characteristics, advantages and potential challenges of each hybrid process are also summarized. Compared to the standalone methods, hybrid processes showed the superiority not only in CO_2 recovery and energy penalty, but also in the installation investment. Therefore, hybrid processes can be a promising alternative to conventional CO_2 capture technologies in future.

1. Introduction

Climate change caused by greenhouse gas emission has attracted increasing concern. In 2012, global CO_2 emission was approximately 3.17×10^{10} t, as shown in Fig. 1 [1]. China is the largest CO_2 emission country (totally 8.25×10^{9} t) in the world. Combustion of fossil fuels is the dominant contributor for anthropogenic CO_2 emission. According to the report of International Energy Agency (IEA), fossil fuels still account for over 80% of the world energy supply [1]. In China, about 70% of energy is provided by coal and petroleum. The resulting greenhouse gas effect has become more serious in recent years, which greatly affected ecological balance. Therefore, it is urgent to develop effective CO_2 mitigation technologies.

Using clean energy instead of fossil fuels is an effective strategy to mitigate CO_2 emission. However, it is difficult to optimize the structure of energy source in a short term. CO_2 capture and storage (CCS) is a promising countermeasure against global warming. Depending upon different plant configurations, CO_2 emission from flue gas of thermal power plant can be reduced by three strategies, including pre-combustion capture, post-combustion capture, and oxy-fuel combustion [2,3]. The detail CO_2 capture technologies generally include absorption, adsorption, membrane, cryogenic and hydrate etc. [4]. Nevertheless, the retrofit of CCS units into a power plant would cause a significant decrease in electric output [5]. Merkel et al. reported that an amine system used to capture 90% of CO_2 in flue gas would require about 30% of the power produced by the plant and result in a CO_2 capture cost of 40–100$ per ton CO_2 [6]. Therefore, reducing the energy requirement of capture is critical to a large-scale commercial application of CCS technology.

Recent years, combination of two or more standalone CO_2 capture technologies, named as hybrid processes, has attracted more and more attention due to the potentially high capture efficiency and low energy requirement. This work is objective to provide a state-of-the-art of hybrid CO_2 capture processes. At the beginning, the challenges of existing CO_2 capture technologies are introduced. Then, the hybrid CO_2 processes mentioned in the literatures are classified in four types, including

* Corresponding author at: Tianjin Key Laboratory of Indoor Air Environmental Quality Control, School of Environmental Science and Technology, Tianjin University, 135 Yaguan Road, Haihe Education Park, Tianjin, China.
E-mail address: chunfeng.song@tju.edu.cn (C. Song).

http://dx.doi.org/10.1016/j.rser.2017.09.040
Received 7 October 2016; Received in revised form 27 July 2017; Accepted 14 September 2017
Available online 22 September 2017
1364-0321/ © 2017 Elsevier Ltd. All rights reserved.

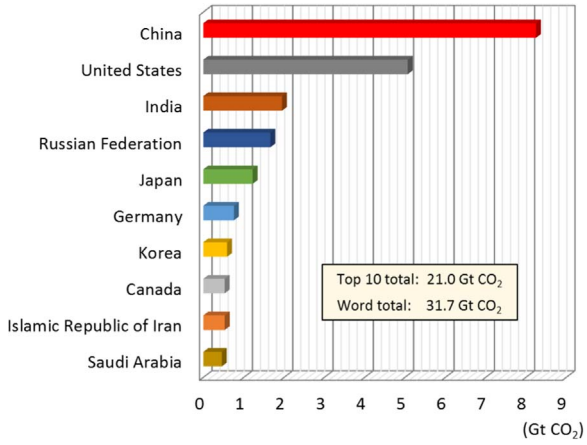


Fig. 1. Top 10 CO2 emission countries in the worldwide in 2012 [1].

absorption based, adsorption based, membrane based and cryogenic based hybrid process. The characteristics (such as source of raw gas, application condition, and CO_2 capture performance) of each hybrid process are investigated and summarized. An overall comparison of advantages, challenges and potential solutions of each hybrid process is then carried out. Finally, the future trends of hybrid CO_2 capture processes are also discussed.

2. Challenges of current CO_2 capture processes

At present, the major challenge of existing CO_2 capture technologies is high energy consumption. For example, as one of the most mature technologies, the energy requirement for solvent regeneration of MEA absorption process varies from 3.0 to 4.5 MJ/kg CO_2, which contributes around 80% of the total energy consumption [7,8]. According to the annual report of National Energy Technology Laboratory (NETL), integrating of CO_2 capture unit (i.e. MEA absorption) into coal-fired power plant would lead to the decrease of total efficiency from 35% to 24.4%, and capturing per ton CO_2 approximately consumed 80 US dollar [9]. Sipöcz and Tobiesen evaluated the economic analysis of a 440 MWe natural gas combined cycle power plant with an integrated CO_2 removal plant, using an aqueous solution of monoethanolamine (MEA) [10]. Simulation results indicated that net LHV efficiency decreased from 58.29% to 49.48%. Goto et al. reviewed recent studies on the efficiency penalty of coal-fired power plants with CCS [5]. The investigation results indicated that the efficiency penalty for current technologies was about 10%. By reducing the regeneration energy of the CO_2 scrubbing solvent by 1 GJ/ton CO_2, an approximate 2% efficiency improvement can be expected.

Clausse et al. mentioned that the energy consumption of CO_2 capture processes has to be reduced as low as possible (target around 1 GJ/ton CO_2 is sometimes quoted) while keeping high CO_2 recovery (above 90%) [11]. Chemical absorption (conventional MEA) is often defined as a reference process. The heat requested for the amine regeneration, in up to date MEA processes, represents an energy cost ranging from 2.5 to 3.5 GJ/ton CO_2 [8,12]. A recent study by Ho et al. showed that the cost of CO_2 capture (in 2008 terms) from a 500 MW subcritical lignite power plant is over US$70 per metric ton of CO_2 using commercially available 30 wt% MEA solvent. When advanced heat integration with the power plant is applied, the capture cost decreases to US$55 per metric ton of CO_2 avoided [13]. As a comparison, the carbon tax of Australia in 2012 was A$23 per metric ton of CO_2 and the European Union Emissions Trading System (ETS) carbon price was €3.5 per metric ton of CO_2, which means that the current cost of implementing CCS is higher than both the Australian carbon tax and the EU carbon credit price [14,15]. In addition, the application of CCS is also restricted by some specific drawbacks, such as the degradation of solvent, secondary pollution, installation corrosion, high material cost, non-stability selectivity etc. [16,17]. Table 1 summarized the existing challenges of dominant CO_2 capture processes.

3. Hybrid CO_2 capture processes

So far, the development of CO_2 capture processes has largely focused on single separation technologies (absorption, adsorption, membranes, cryogenics, etc.). A few studies examined the merits of combining different separation technologies into a hybrid capture process [41]. To overcome the challenges of standalone CO_2 capture technologies, hybrid processes may be a potential alternative. It usually consists of two or more conventional technologies (i.e. absorption, adsorption, membrane, cryogenic and hydrate etc.). The integration of different technologies may be superior to the standalone process, and avoid their disadvantages [42].

Potential hybrid CO_2 capture processes can be classified into four categories, such as absorption-based, adsorption-based, membrane-based and cryogenic-based hybrid processes. Meanwhile, each category also includes different options in process arrangement, as shown in Fig. 2. A total of 7329 publications on hybrid CO_2 capture technologies in the last decade were depicted in Fig. 3. Among them, approximately 60% (4383 publications) belonged to absorption based hybrid processes, 20% (1448 publications) belonged to adsorption based hybrid processes, 16% (1163 publications) belonged to membrane based hybrid processes, and 4% (335 publications) belonged to cryogenic based hybrid processes.

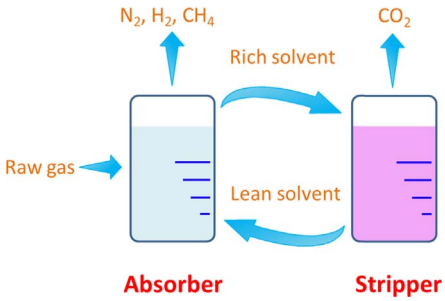
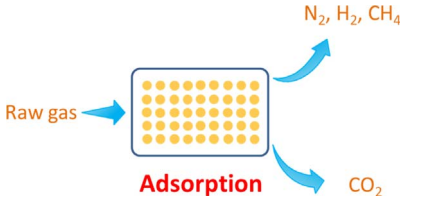
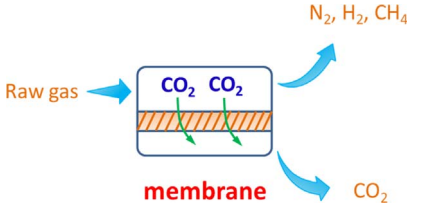
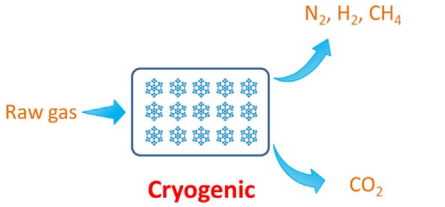
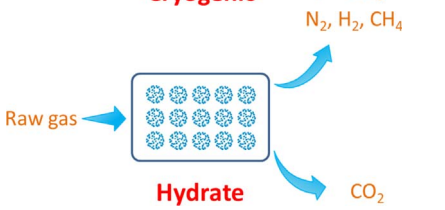
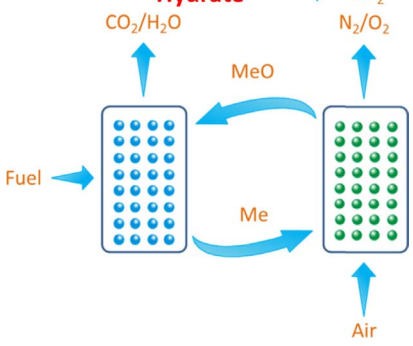
Screening of suitable hybrid CO_2 capture processes highly depends on the properties of feed gas (e.g. CO_2 concentration, gas temperature and pressure etc.), the requirement of product (e.g. purity etc.) and the availability of the capture equipment. In addition, CO_2 recovery and energy consumption are also significantly affected by the source of CO_2 emission when using different capture technologies. It should be noted that for various technologies the types of required energy are different [43,44]. For example, there are two main energy factors that should be considered in the typical MEA absorption processes. One is the thermal energy used for regenerating the solvent and extracting steam from the steam turbine, which dominates the energy consumption of the whole capture process. The other is the electric energy for the machine operation. In the adsorption processes, the type of energy is decided by the way of desorption. Electric energy is dominant in pressure swing adsorption (PSA) to generate pressure difference, and thermal energy is used in temperature swing adsorption (TSA) to provide desorption heat. In membrane gas separation, all the energy required is electric energy to drive compressor or vacuum pump. In the cryogenic and hydrate separation processes, both the cryogenic and high pressure condition and operation of the systems are based on electric energy consumption.

3.1. Absorption-based hybrid processes

3.1.1. Membrane contactor

Membrane contactor is one of the most common hybrid technologies, which is widely applied in CO_2 capture processes. It is different from the conventional membrane process, which separates gases by selective permeation through a dense membrane separation layer by a solution/diffusion mechanism [45]. The different configuration of membrane contactors is illustrated in Fig. 4. The separation driving force is provided by the partial pressure difference of each gas component across the membrane. The conventional membrane processes require either flue gas compression, permeate side sweep, application of permeate-side vacuum, or a combination of these steps to provide the separation driving force. The integration of absorption and membrane has the benefits of both liquid absorption (high selectivity) and membrane separation (modularity and compactness), and is more effective at low CO_2 concentration [46–48]. The major disadvantage of membrane contactors is the increased mass transfer resistance, especially

Table 1
Existing challenges of dominant CO_2 capture technologies.

CO_2 capture technologies	Schematic diagram	Existing challenges	References
Absorption		• Large energy penalty for regeneration • Additional compression work requirement for the captured CO_2 transportation and storage • High equipment corrosion rate • Degradation of solvent (i.e. amine) • Negative environmental impact of solvent emission	[18–21]
Adsorption		• Challenges in handling solid • Relatively low CO_2 selectivity • Low adsorption rate • Sorbent degradation and attrition in cyclic operation • Intermittent operation and it needs periodic regeneration of the adsorbents • Pressure drop can be large in flue gas applications	[22–25]
Membrane		• Requirement of compression work for driving force • High membrane manufacturing cost • Requirement of high selectivity (due to CO_2 concentration and low pressure ratio) • Fouling effect • High membrane surface area is required to accommodate the high flow rate of industrial flue gas • Moisture adversely affected the permeability of polymeric membrane • Performance is affected by operating condition (i.e. temperature and pressure)	[6,25–29]
Cryogenic		• High energy requirement to provide sufficient refrigeration • More suitable for high CO_2 concentration, typically higher than 50% • Moisture must be removed from the gas mixture before cooling in order to prevent blockage caused by ice particles • Continuous build-up of solidified CO_2 on heat-exchanger surfaces adversely affect heat transfer and reduces the process efficiency	[30–33]
Hydrate		• CO_2 capture efficiency is adversely affected with other molecules trapped in the cage structures • Requirement of high pressure and low temperature • Secondary pollution of promoter	[34–37]
Chemical looping combustion (CLC)		• Decay of sorbent reactivity during capture/regeneration cycles • High attrition rate and vulnerability • High investment of installation cost • Requirement of an air separation unit to obtain pure O_2 for calcination	[38–40]

when membranes are wetted [49].

3.1.2. Absorption-membrane process

Apart from membrane contactor, combination of absorption and membrane in series or parallel arrangement are also promising methods of hybrid CO_2 capture, as shown in Fig. 5. The hybrid processes offer the potential for two modes of cost savings, the reduction of regeneration energy in the series arrangement and the reduction of capital costs in the parallel arrangement [41]. In series arrangement, the absorber operates at a higher lean-loading state and also benefits from the ability of the downstream membrane to mitigate negative amine emission. As a result, the absorber removes approximately half of the CO_2 in the flue gas, followed by additional separation by the membrane contactor to achieve 90% total removal of CO_2. In the

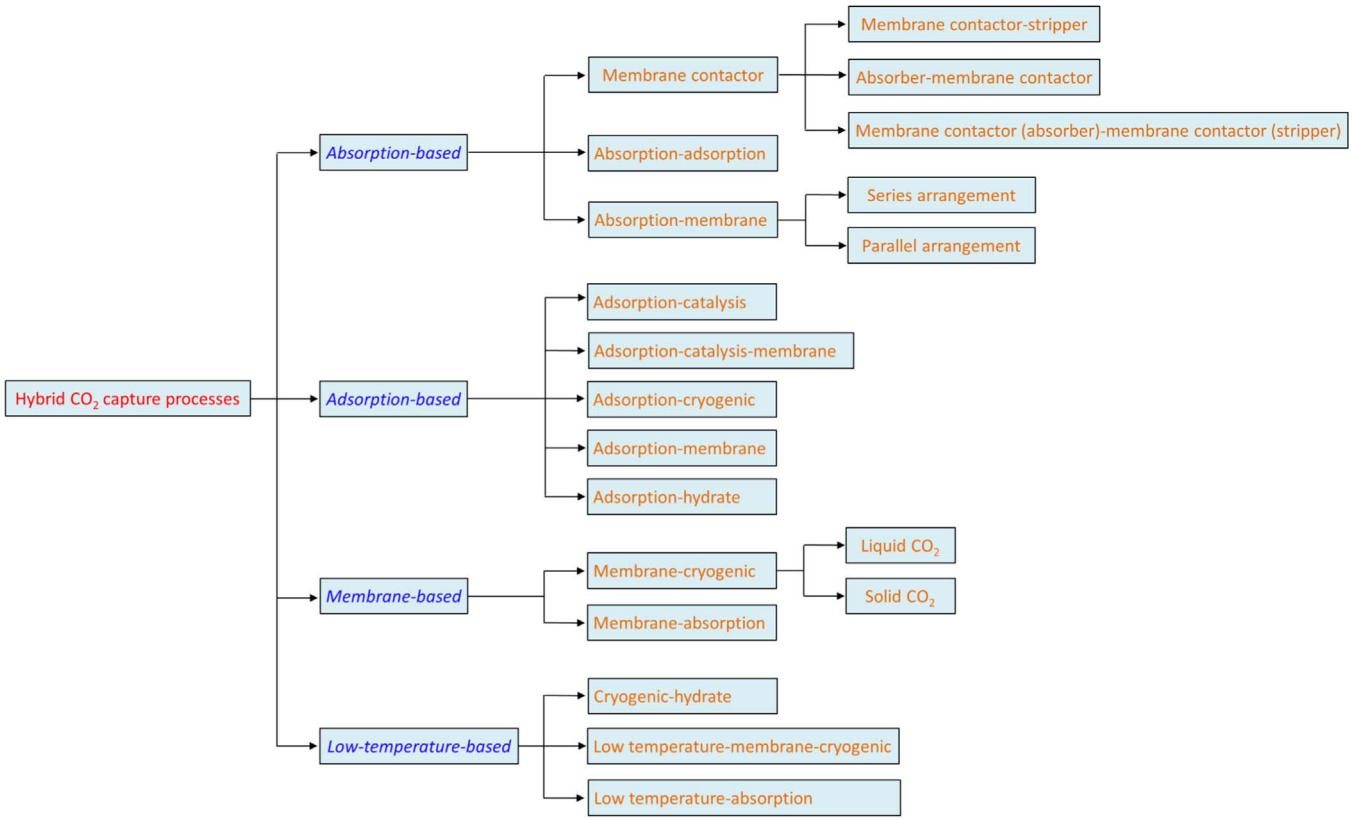


Fig. 2. Existing hybrid CO_2 capture processes.

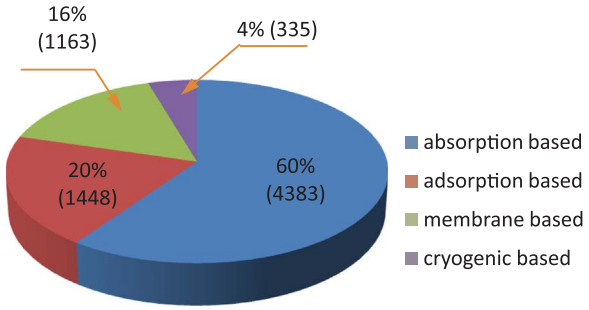


Fig. 3. Number of publications related hybrid CO_2 capture processes in the last decade (from 2008 to 2017).

parallel configuration, the flue gas from the power plant is split and treated by membrane and absorption in a parallel arrangement. The principal advantage is that the absorber can be roughly half the size it would normally be.

In addition, the use of boiler combustion air as a sweep gas on the membrane permeated side can also contribute to efficient CO_2 capture [50]. It can generate the driving force by passing rich CO_2 flue gas at the same pressure across the membrane feed side. In this way, the partial pressure of the carbon dioxide on the permeate side is maintained lower than the feed side. CO_2 then passes from the flue gas into the sweep air stream that goes to the boiler. The treatment is beneficial to enrich the CO_2 content in the flue gas from 13% to 23%, under the common operational conditions of a coal fired power plant.

3.1.3. Absorption-adsorption process

The key of absorption-adsorption hybrid CO_2 capture technology is advanced sorbent materials. The typical one is amine-enhanced sorbents, which has been developed by National Energy Technology Laboratory (NETL) [51]. As shown in Fig. 6, the principle of absorption-adsorption hybrid process is to separate CO_2 from gas stream by carbon, silica or polymer supports integrated with amine compounds [52,53]. The CO_2 absorbed on the amine sites is subsequently released upon increasing the temperature (TSA) or pressure variation (PSA). This process has some advantages over the conventional absorption or adsorption standalone process, e.g., higher CO_2 carrying capacity, lower heat capacity (as there is no water to heat). One technical challenge is that small particle diameters can cause a high-pressure drop across the absorber. The sorbent regeneration energy has been estimated at 1.44 GJ/ton CO_2, which would be a breakthrough improvement over the current state-of-the-art of about 3.72 GJ/ton CO_2 [51].

Table 2 presents a comprehensive summary of various absorption based hybrid CO_2 capture processes so far, and the application performance at different CO_2 emission sources. As one of the most common hybrid processes, membrane contactor can achieve high CO_2 recovery with competitive energy requirement of solvent regeneration. Absorption-membrane hybrid process also shows the potential in post combustion CO_2 capture. The CO_2 recovery and purity is drastically changed with the properties of materials in absorption-adsorption process. However, the capture efficiency and process stability will be improved when new sorbent is developed.

3.2. Adsorption-based hybrid processes

3.2.1. Adsorption-catalysis processes

In pre-combustion process, CO_2 is required to be separated from H_2 product after gasification treatment. Compared with the conventional PSA or membrane H_2 purification processes, the sorption enhanced water gas shift (SEWGS) reaction process can combine a high temperature water gas shift (WGS) catalyst and a CO_2 sorbent in the same reactor, as shown in Fig. 7 [57,58]. The hybrid system allows an increase in the conversion of CO due to the removal of one of the products (CO_2) by the sorbent. The presence of the adsorbent with the catalyst allows the simultaneous occurrence of two processes in one single

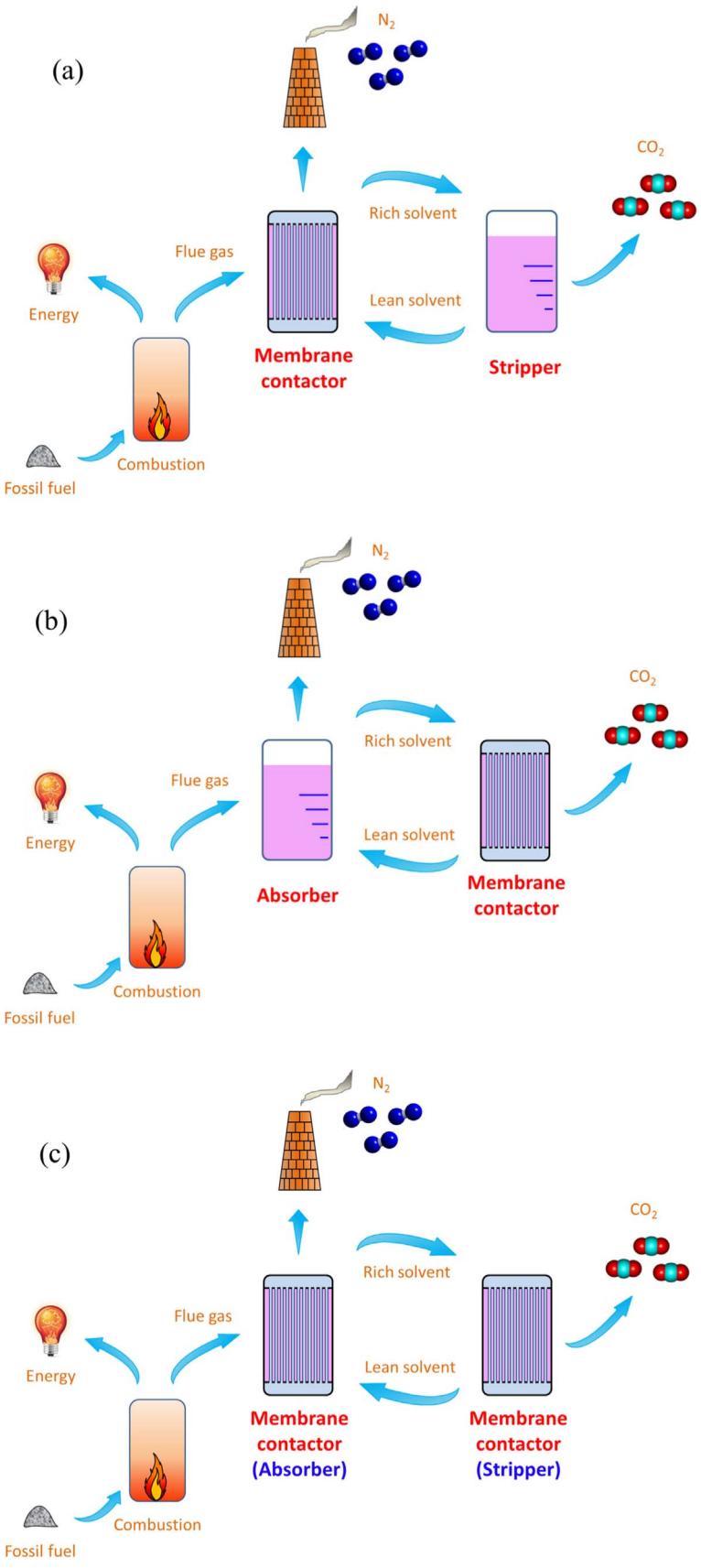


Fig. 4. Membrane contactor CO_2 absorption processes [45]. (a) membrane-striper, (b) absorber-membrane, (c) membrane (absorber)-membrane (stripper).

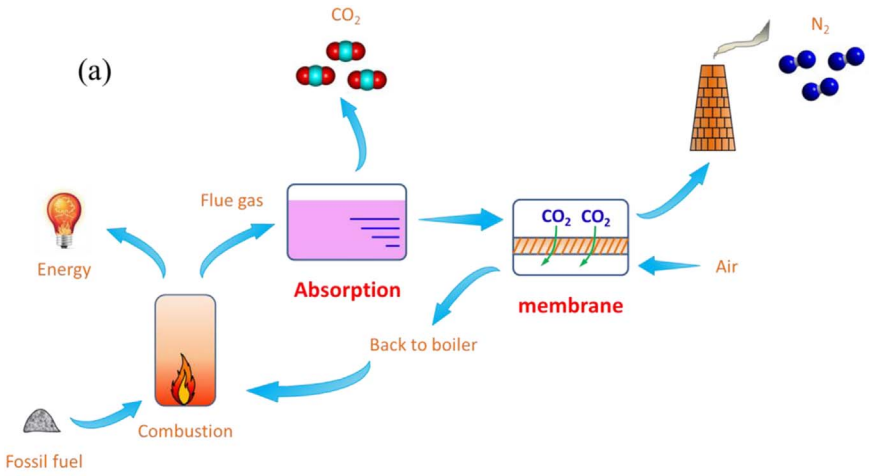


Fig. 5. Absorption-membrane hybrid CO2 capture processes. (a) series arrangement, (b) parallel arrangement [41].

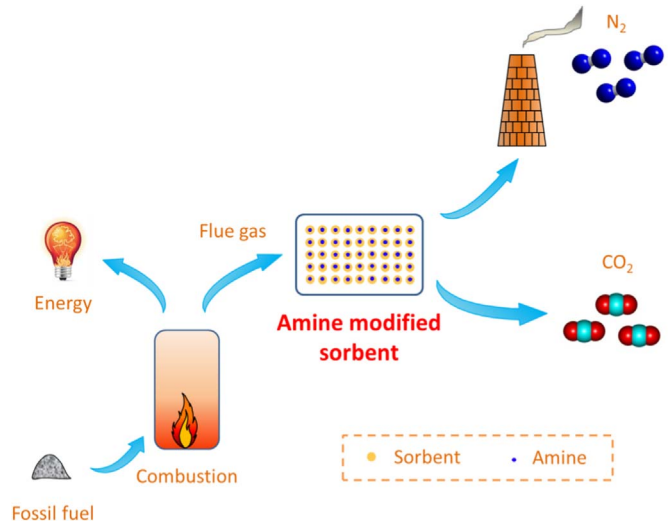


Fig. 6. Absorption-adsorption hybrid CO2 capture process [52,53].

reactor at high temperature, and avoids the need of a second reactor in the conventional WGS process [59]. Thus, the H_2 productivity can be obviously enhanced. Moreover, the capital cost is reduced by simple equipment investment.

3.2.2. *Adsorption-catalysis-membrane processes*

Although the sorption-enhanced-water-gas-shift (SEWGS) reaction can directly produce higher purity H_2 than a conventional catalyst-only reactor, it is not high enough to satisfy high purity application (> 99.9%) [60]. One of the promising options to produce ultrapure H_2 is combining the membrane reactor with the SEWGS, which is also named as sorption-enhanced-water-gas-shift-membrane-reactor (SEWGSMR), as shown in Fig. 8. The continuous removal of H_2 from the reaction media by permeation through the membrane enhances the conversion of CO to CO_2 and H_2. The SEWGSMR process has several significant advantages [60–62]. For example, the process may be performed in a single unit, which simplifies the overall hydrogen production configuration. Compared to the standalone membrane reactor, it allows decreasing the required membrane area, which often leads to high capital cost. The reaction may be conducted with a lower H_2O/CO ratio, thereby reducing steam usage and operational cost. Finally, high purity H_2 can be directly produced with simultaneously high CO_2 capture efficiency. Up to now, dense Pd and Pd alloy based membranes are potential candidates as a H_2 highly selective membrane [61,63,64].

3.2.3. *Adsorption-cryogenic processes*

Adsorption-cryogenic process is an emerging and promising hybrid technology for CO_2 capture. Fong et al. designed a vacuum swing adsorption and low-temperature hybrid CO_2 capture process, as shown in Fig. 9 [65]. In the hybrid process, a vacuum swing adsorption (VSA) unit was used as the initial stage of CO_2 recovery. Then, the high concentration CO_2 was further separated in liquid form by a low-

Table 2
Performance comparison of different absorption based hybrid CO_2 capture processes.

Processes	Source of feed gas	CO_2 recovery (%)	CO_2 purity (%)	Energy consumption (GJ/ton CO_2)	References
Membrane contactor	Post-combustion (13.4% CO_2, 71.8% N_2, 4.5% O_2, 9.5% H_2O)	90	—	0.86 (electric energy)	[54]
	Post-combustion (13–16% CO_2, 84–87% N_2)	90	97	1.2–3.5 (thermal energy)	[45]
Absorption-membrane	Post-combustion (20% CO_2, 80% N_2)	90	—	1.90 (thermal energy)	[41,55]
Absorption-adsorption	Post-combustion (15% CO_2, 85% N_2)	50.4~ 98.5	85–100	1.6–2.0 (thermal energy)	[52,56]

temperature unit. The investigation results showed that the total energy consumption of adsorption-low-temperature process can be reduced to 1.40 GJ/t CO_2, with an overall CO_2 recovery rate of 88.9% [65]. In addition to energy consumption, several advantages were also observed. First, a high purity CO_2 stream can be obtained. Second, liquid CO_2 product can be pumped to the supercritical state required for transportation and sequestration. Third, the conventional multi-stage CO_2 compression unit was replaced with a low-temperature and pressurizing step, which contributed to energy saving.

3.2.4. Adsorption-membrane processes

Biogas upgrading from digesters allows production of high quality bio-natural gas and reduction in CO_2 emissions [66]. Commonly, raw biogas contains approximately 30–45% CO_2 and 50–65% CH_4 [67]. The dominant purification methods of biogas include water washing, membrane separation, chemical absorption and pressure swing adsorption [68–70]. Although CO_2 separation from biogas is easier than the flue gas from power plants due to high concentration, the disadvantages (e.g., high energy requirements) of standalone technologies still exist [71,72]. To enhance the biogas upgrading efficiency, a two-stage membrane process, coupled with a temperature-swing-adsorption (TSA) as pre-treatment, was designed to generate pipeline quality methane [73]. The schematic diagram is shown in Fig. 10. During the process, the non-product streams of the membrane process were recycled to improve methane recovery and process energy efficiency, and the permeation of the first membrane stage was maintained at a given pressure as the driving force for second membrane stage. The detailed investigation results indicated that biogas yield achieved 97% methane purity with 0.67% losses and a CO_2 stream of 99% purity and 95.5% recovery [73].

3.2.5. Adsorption-hydrate processes

Hydration can be utilized for CO_2 capture and separation from either post-combustion flue gas or pre-combustion flue gas. Gas hydrates are ice-like crystalline inclusion compounds formed by hydrogen-bonded water molecules and small gas molecules (such as CH_4, C_3H_8, and CO_2) at low temperature and high pressure conditions [74,75]. To improve hydrate formation kinetics and increase gas consumption, the combination with high selective sorbents is considered as an effective innovation, as shown in Fig. 11. Typically, a fixed bed reactor filled with porous media such as silica sand [76], silica gel [77,78], and activated carbon [79,80] was employed, where mass transfer between gas and liquid phase was enhanced due to the huge specific surface area of porous media, and energy cost on the mechanical agitation in stirred reactors was saved [81].

The application of absorption based hybrid CO_2 capture processes is reported in Table 3. For the synthesis gas from gasification or reforming, adsorption-catalysis and adsorption-catalysis-membrane hybrid processes demonstrate significant advantages due to high product quality and catalytic conversion. For the dilute CO_2 from post-combustion, adsorption-cryogenic process can be used to balance the CO_2 recovery and energy consumption. In addition, adsorption-membrane and adsorption-hydrate processes have specific potential in biogas and shale gas upgrading.

3.3. Membrane-based hybrid processes

3.3.1. Membrane-cryogenic processes

Combining membrane with conventional separation processes in membrane based hybrid CO_2 capture processes can merge the advantages of both technologies. As a typical membrane based hybrid process, membrane-cryogenic process has attracted broad attention. Fig. 12 illustrates the schematic diagram of membrane-cryogenic hybrid process. Anantharaman et al. developed a hybrid membrane–liquefaction process for post-combustion CO_2 capture from the power plant flue gas [84]. In the hybrid process, the concentration of CO_2 in flue gas was firstly increased to 50~75% by membrane unit. Then, the rich CO_2 stream was compressed by two-stage vapor compression

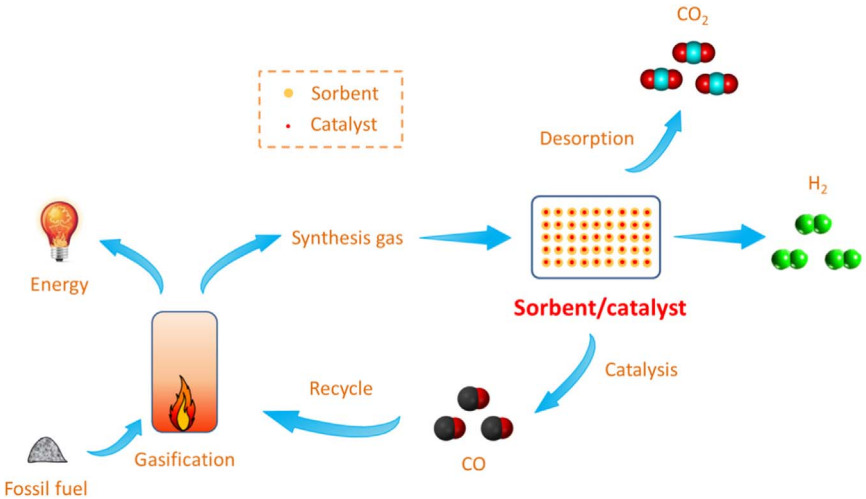


Fig. 7. Adsorption-catalysis hybrid CO2 capture process [57,58].

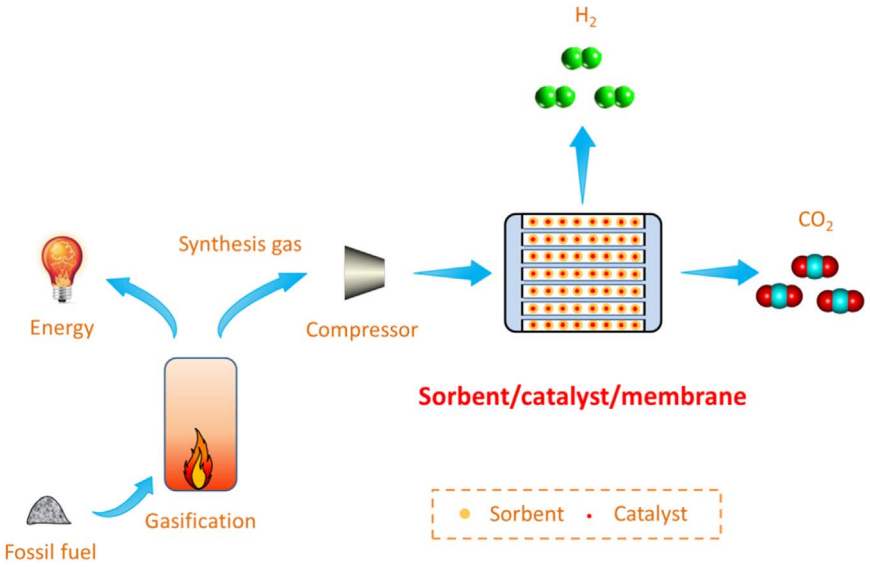


Fig. 8. Adsorption-catalysis-membrane hybrid CO_2 capture process [60].

cascade cycle. Propane and ethane were used as refrigerant to condense CO_2 in the liquid form. Compared with the standalone membrane process (two-stage), the requirement of compression work could be decreased in the hybrid process. The techno-economic analysis indicated that the cost of CO_2 avoided of hybrid process was reduced to 48 $€_{2008}/tCO_2$ (with 85% CO_2 capture ratio), which was 9% more cost-efficient than the reference MEA absorption process.

Burdyny and Struchtrup proposed a hybrid membrane-cryogenic separation method for use in the oxy-fuel process [85]. The designed process uses an O_2/N_2 permeable membrane to create oxygen enriched air. Then, the enriched air is turned into high purity oxygen using cryogenic distillation. Compared to the standalone cryogenic distillation process, the capital cost of hybrid membrane-cryogenic method could be reduced by using small size cryogenic equipment, compressors, pipes and distillation columns. In addition, the operation cost could also be saved due to the variation of operation condition (i.e., decrease of initial compression pressure and internal temperature of distillation column). As a result, hybrid technology on the oxy-fuel combustion was found to improve the process efficiency by 0.9% [85].

Belaissaoui et al. also investigated the feasibility of hybrid process combining membrane and cryogenic separation to achieve efficient post-combustion carbon capture [86]. The hybrid process combines a first step CO_2 pre-concentration by membrane separation with a second step CO_2 cryogenic condensation (liquid product). For CO_2 feed concentration ranging between 15% and 30%, the hybrid process showed a reduced energy requirement compared to the reference chemical absorption technology (MEA as solvent). The energy requirement of hybrid process was lower than 3 GJ/ton CO_2 (including compression of CO_2 to 110 bar), with CO_2 recovery ratio above 85% and CO_2 purity above 89% [86].

3.3.2. *Membrane-absorption process*

The potential of using a membrane–amine hybrid process for post-combustion CO_2 capture has not been well addressed in the open literatures, except in quite few cases. Kundu et al. reported a membrane-absorption hybrid CO_2 capture process, as shown in Fig. 13 [87]. Most of CO_2 in the feed gas was recovered by the membrane unit. Meanwhile, the retentate stream from the membrane unit (having been depleted of CO_2) was fed to the amine unit to match the desired recovery (85%) of the overall hybrid process. High purity (98%) CO_2 can be obtained from membrane unit which is mixed with the outlet stream of the amine unit. In the membrane-absorption hybrid process, the heat duty of reboiler at the bottom of stripper can be significantly saved due to a moderate increase in the membrane area. As a result, the total energy penalty of the hybrid process thus decreases as more share of CO_2 is removed by the effectiveness membrane.

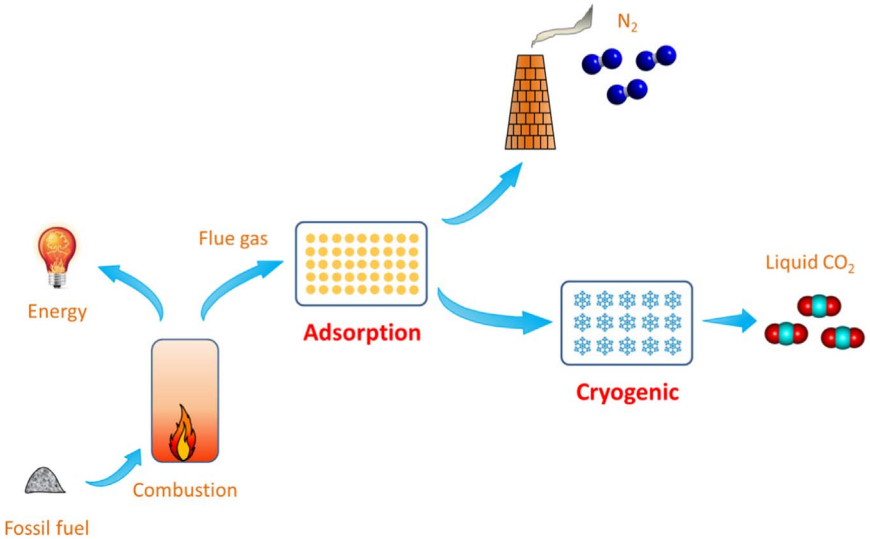


Fig. 9. Adsorption-cryogenic hybrid CO_2 capture process [65].

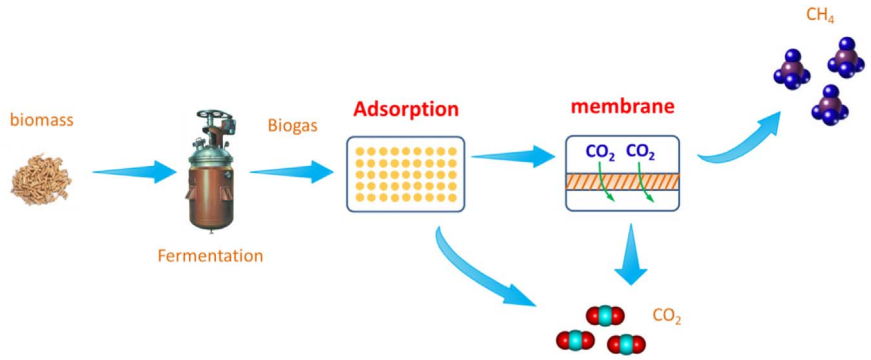


Fig. 10. Adsorption-membrane hybrid CO2 capture process [73].

Table 4 lists a comprehensive evaluation of various membrane based hybrid CO_2 capture processes and their application in different emissions. Membrane-cryogenic is one of the most popular membrane based hybrid CO_2 capture processes, which shows a promising capture performance in different CO_2 emissions (e.g., post-combustion capture and biogas upgrading). Membrane-absorption hybrid process can also be applied to CO_2 concentration in the range of 15–36%, and CO_2 recovery and purity are both competitive. However, the energy consumption needs to be further reduced. In addition, membrane-water scrubbing, as a specific biogas upgrading method, presents both high CH_4 purity and low energy consumption.

3.4. Low-temperature-based hybrid processes

3.4.1. Cryogenic-hydrate processes

The necessary conditions for both cryogenic and hydrate CO_2 capture technologies are low temperature and high pressure. Thus, there is a potential to design a cryogenic-hydrate hybrid CO_2 capture process [89]. The schematic diagram of cryogenic-hydrate hybrid process is shown in Fig. 14. The first stage is condensation by cryogenic at −55 °C where CO_2 concentration is expected to be reduced by up to 75 mol%. Remaining CO_2 is captured in the form of solid hydrate at about 1 °C reducing CO_2 concentration down to 7 mol%. Compared with the conventional standalone cryogenic distillation processes (−73.3 °C), the cryogenic-hydrate CO_2 capture technology showed the potential for reduction of CO_2 emissions at lower cost and energy requirement [90]. To enhance the hydrate formation and reduce the equilibrium conditions (e.g. high pressure), promoters are usually used in hydrate unit, such as TBAB (tetrabutylammonium bromide), TBAC (tetrabutylammonium chloride), TBAF (tetrabutylammonium fluoride), TBPB (tetrabutylphosphonium bromide), THF, TBPC (tetrabutylphosphonium chloride), and $TBANO_3$ (tetrabutylammonium nitrate) etc. [37].

3.4.2. Low temperature-membrane-cryogenic processes

Ambient temperature has a significant influence on the performance of gas separation membrane. Usually, permeability of membrane decreases and selectivity increases with the decrease of operating temperature [91]. However, the hollow fiber membrane developed by Air Liquide, Inc. showed two to four times (compared to ambient temperature values) increase in CO_2/N_2 selectivity with minimal CO_2 permeance loss when operated at temperature below −20 °C [91]. Based on the characteristic of the cold membrane, Air Liquide, Inc. developed a low temperature-membrane-cryogenic hybrid CO_2 capture process, as shown in Fig. 15. Long term (6 month) bench-scale testing with CO_2/N_2 mixtures at sub-ambient conditions has verified the enhanced separation performance seen at lab scale translated to commercial membrane modules [91,92].

3.4.3. Low temperature-absorption processes

Monoethanolamine (MEA) is regarded as the reference chemical solvent, as it can probably be used in the early stage commercial scale post-combustion CO_2 capture plants [93]. The disadvantages of using MEA as a solvent are high energy penalty caused by rich solvent regeneration, thermal degradation, formation of heat-stable salts, and oxidation caused by O_2 [94–96]. The hybrid of low temperature and aqueous NH_3 has been considered as one of the most promising alternatives to overcome the challenges of MEA absorption, named as chilled ammonia process, as shown in Fig. 16 [97]. Typically, the chilled ammonia process absorbs the CO_2 at the temperature range from 2 °C to 10 °C. Compared with MEA, NH_3 appears several significant features to be an effective CO_2 solvent, including relatively low price, commercial availability, low energy for regeneration, non-corrosive and comparatively high CO_2 absorption capacity [97,98]. In addition, the combination with low temperature units can effectively avoid the volatility of NH_3 in the absorber [99].

Table 5 presents a comprehensive summary of various cryogenic based hybrid CO_2 capture processes and their application in different raw gas. Cryogenic-hydrate hybrid process shows the potential of high CO_2 purity in pre-combustion CO_2 capture. However, before large scale application, the kinetic and thermodynamic properties of each promoter should be further investigated to better understand the dissociation of CO_2 hydrate [36]. Low-temperature-membrane-cryogenic process can capture CO_2 from post-combustion flue gas with low energy

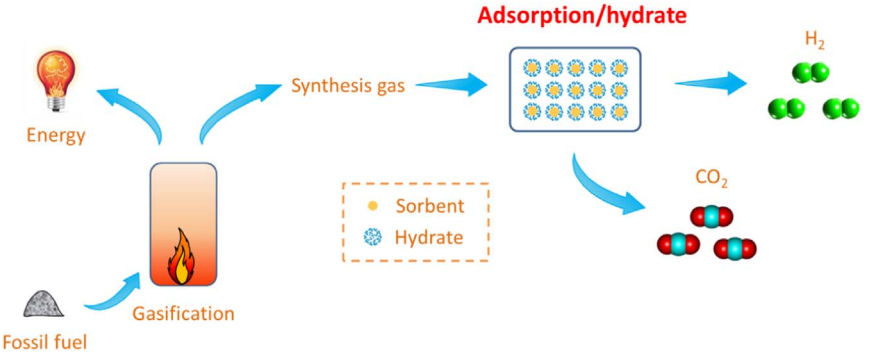


Fig. 11. Adsorption-hydrate hybrid CO2 capture process [76,77].

Table 3
Performance comparison of different absorption based hybrid CO_2 capture processes.

Processes	Source of feed gas	CO_2 recovery (%)	CO_2 purity (%)	Energy consumption (GJ/ton CO_2)	References
Adsorption-catalysis	Pre-combustion (5% CO, 24% CO_2, 36% H_2, 30% H_2O, 4.4% N_2)	95 (H_2)	99 (H_2)	—	[82]
Adsorption-catalysis-membrane	Pre-combustion (5% CO/N_2, 50% steam)	97 (H_2)	99.83 (H_2)	—	[62]
Adsorption-cryogenic	Post-combustion (11.4% CO_2, 88.6% N_2)	88.9	> 95	1.4 (electric energy)	[65]
Adsorption-membrane	Biogas (40% CO_2, 60% CH_4)	95.5	99	1.69 (CH_4/electric energy)	[73]
Adsorption-hydrate	Pre-combustion (40% CO_2, 60% H_2)	40.4–57.9	89.3–99.1	—	[83]
	Shale gas (40% CO_2, 60% CH_4)	52.3	60	—	[81]

consumption by taking advantage of cold membrane properties. Chilled ammonia absorption has a high CO_2 recovery when utilized into post-combustion CO_2 capture. However, the energy consumption of regeneration should be further reduced.

3.4.4. Phase of CO_2 product

In cryogenic-based hybrid processes, CO_2 can be captured in different phases, e.g. vapor-liquid (CO_2-rich liquid phase), vapor-solid (solid CO_2) or a combination such as CO_2 slurry. Liquid CO_2 product needs both the cryogenic temperature and high pressure condition. Solid CO_2 product is usually obtained under a lower temperature than that of liquid form. It is obvious that the state of CO_2 product significantly affects the energy consumption of the overall processes. However, to save energy, an optimal heat integration treatment can be used to recover the cold energy and high pressure along with the cold product and residual stream. Therefore, it is necessary to investigate the capture conditions and thermodynamic characteristics for each process [44].

In addition to CO_2 capture section, the convenience of transportation or utilization should also be considered. Liquid CO_2 product with high pressure is the easiest form to be transport [100]. Although the capture cost of the anti-sublimation process is low, the transport cost will increase dramatically in solid form [101]. Therefore, it would be a promising strategy to transfer the deposited CO_2 into the gas or liquid phase before transportation and recover the sensible and latent heat.

4. Advantages of hybrid CO_2 capture processes

4.1. Absorption-based hybrid processes

Some literatures evaluated the advantages of hybrid CO_2 capture processes compared to the standalone processes. The notable advantages can be summarized based on the results of previous research, as listed in Table 6.

Hollow fiber membrane contactors for CO_2 capture provide a high surface area/volume ratio for the separation to take place [103–105]. This leads to a mass transfer coefficient that is 5–10 times greater than that achieved in a conventional tower or column with trays or packing. Thus, the use of a membrane contactor instead of a conventional amine scrubber tower leads to a much smaller space requirement. This technology is well-suited for new and existing pulverized coal-fired power plants due to the reduced footprint requirement and a much lower visual impact as well as providing more options for placement in the confines of existing plants [106].

The hybrid membrane–absorption process offers potential for less stringent capture requirements [87]. In the hybrid process, the permeate-side partial pressure of CO_2 can be considered close to zero due to the chemical reaction of CO_2 with the absorption solvent, and this overcomes the pressure ratio problem encountered by the conventional gas membrane process. Feed compression or permeate vacuum application are not required to create the separation driving force for gas molecules to be transported through the membrane, the process selectivity for the hybrid membrane-absorption process is determined by the chemical affinity of the absorption solvent to CO_2. Therefore, high purity CO_2 product can be obtained in a single stage hybrid membrane-absorption process [45]. In addition, combining membranes and absorption technologies could also result in significant energy savings by reducing the steam required for amine regeneration [107].

4.2. Adsorption-based hybrid processes

H_2 is considered as a green energy compared with fossil fuel, which can be obtained by reforming or gasification processes. Conventional steam reforming is a highly endothermic reaction where typically a

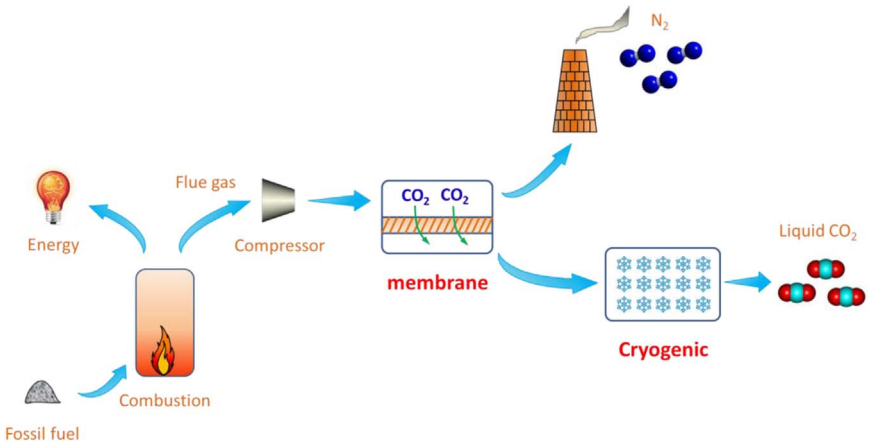


Fig. 12. Membrane-cryogenic hybrid CO2 capture process [84].

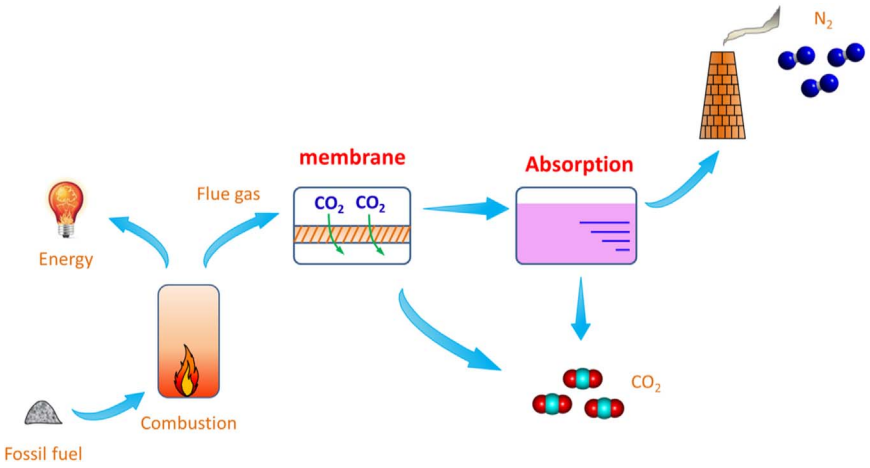


Fig. 13. Membrane-absorption hybrid CO_2 capture process [87].

feeder is reacted with water over the catalysts at high temperature and pressure. In the past few decades, the extensive studies on novel processes have been carried out for high purity H_2 production by in-situ CO_2 capture [108]. Adsorption-catalysis and adsorption-catalysis-membrane hybrid processes are the effective ways to produce highly pure H_2 in a single step [109]. These hybrid processes have several important advantages in comparison with the conventional steam reforming, such as the improvement of energy efficiency and the reduction of capital cost. H_2 can be obtained with a purity of 95–98% (dry basis) and low carbon oxides content, compared to maximum 80% (dry basis) for traditional steam reforming [110]. In adsorption-catalysis and adsorption-catalysis-membrane hybrid processes, further purification is usually not required in most applications. High purity CO_2 stream can also be gathered as by product for storage and utilization.

4.3. Membrane-based hybrid processes

Membrane-based hybrid processes are alternatives to conventional CO_2 capture technologies, which can be used for both post-combustion capture and biogas upgrading. One of the dominant advantages is that gas permeation membranes technology is mature and frequently applied. Compared with absorption based process, gas permeation processes are efficient for moderate purification of gases [111]. To obtain high purity products from a gas permeation module, it requires either a large membrane or strong driving forces, which translates to significant operational costs. Hybrid processes in which membrane technology is combined with conventional gas separation method (i.e. membrane-absorption, membrane-adsorption, membrane-water-scrubbing and membrane-cryogenic etc.) may be superior to the individual processes in which only one single technology (i.e. amine scrubbing, membrane technology) is applied [72,112]. Belaissaoui et al. reported that to achieve a target CO_2 purity of 90 mol%, the energy consumption can be reduced by using a membrane–cryogenic hybrid process as compared to chemical absorption by MEA for a CO_2 feed concentration of 15–30 mol % [86].

It is worth noting that performance of membranes can be affected by operating temperature, which creates the possibility of membrane-cryogenic hybrid CO_2 capture process. In 2013, Liu et al. spun two kinds of asymmetric hollow fiber membranes (fibers with fused nodular skins and fibers with truly dense skins), as shown in Fig. 17 [113]. Permeation results showed that, at −20 °C, the nodular-skinned fibers displayed CO_2/N_2 selectivity of 90.5, and CO_2 permeance of 63.3 GPU (1 GPU = 10^{-6} cm^3 (STP)/cm^2 s cm Hg) after standard PDMS calking. By contrast, the dense-skinned fibers displayed CO_2/N_2 selectivity of 52.5 and CO_2 permeance of 16.6 GPU [114]. When applying nodular skins hollow fiber membrane into low-temperature-membrane-cryogenic hybrid process, it presents the advantages of higher membrane productivity and low membrane unit cost [115].

4.4. Low-temperature-based hybrid processes

The potential advantage of cryogenic based CO_2 capture processes is a high quality CO_2 product can be obtained. In cryogenic based hybrid processes, the condensed liquid CO_2 that can more readily be pumped to a supercritical state relative to gaseous CO_2 that would require a separate compression train [65]. The low-temperature based separation would be ideal as the purification step, since it performs better at high CO_2 concentration feed gas and would also has the potential as a cold

Table 4
Performance comparison of different membrane based hybrid CO_2 capture processes.

Processes	Source of feed gas	CO_2 recovery (%)	CO_2 purity (%)	Energy consumption (GJ/ton CO_2)	References
Membrane-cryogenic	Biogas (36.7% CO_2, 60% CH_4, 3.1% H_2O, 0.2% H_2S)	> 99 (CH_4)	> 96	3.45 (electric energy)	[42]
	Post-combustion (15% CO_2, 85% N_2)	> 85	> 89	< 3.0 (thermal energy)	[86]
	Post-combustion (13% CO_2, 73.4% N_2, 4.6% O2 and 9% H2O)	90	95	0.93 (electric energy)	[88]
	Post-combustion (13.5% CO_2, 70.1% N_2, 3.7% O_2, 11.9% H_2O)	90	98	1.22 (electric energy)	[18]
	Post-combustion	85	—	2.16 (electric energy)	[84]
Membrane-absorption	Post-combustion (15% CO_2, 81% N_2, 4% O_2)	85	98	1.83–3.7 (thermal energy)	[87]
	Biogas (36.7% CO_2, 60% CH_4, 3.1% H_2O, 0.2% H_2S)	99 (CH_4)	> 96	2.15–3.01 (electric energy)	[42]
Membrane-pressurized water scrubbing	Biogas (36.7% CO_2, 60% CH_4, 3.1% H_2O, 0.2% H_2S)	98 (CH_4)	> 96	0.64 (electric energy)	[42]

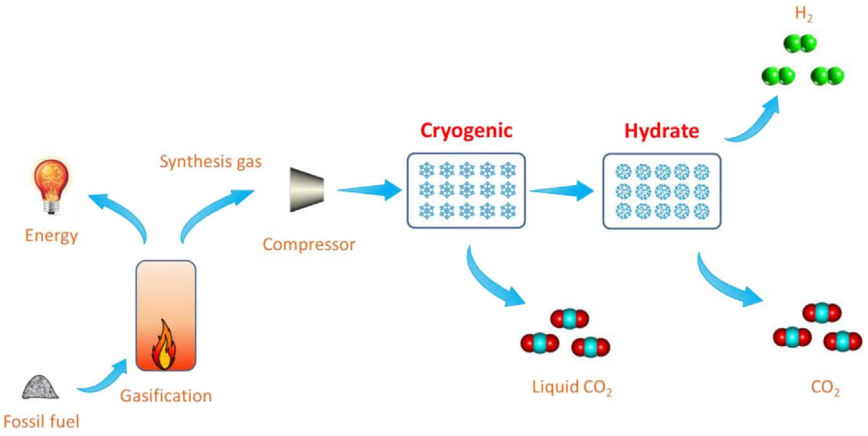


Fig. 14. Cryogenic-hydrate hybrid CO2 capture process [89].

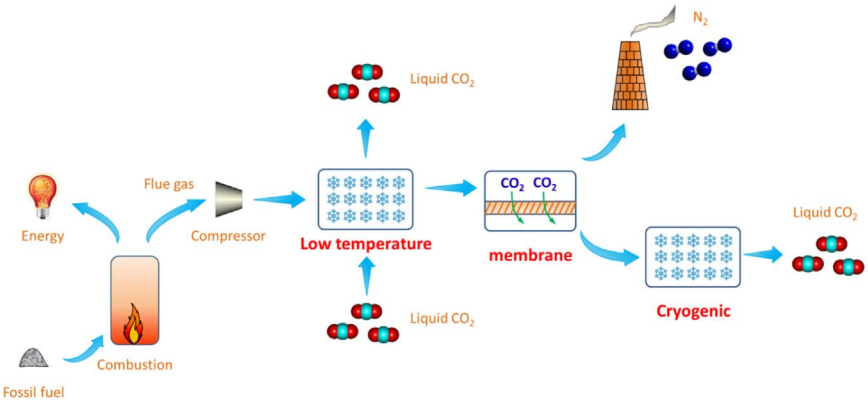


Fig. 15. Low temperature-membrane–cryogenic hybrid CO_2 capture process [91].

energy [116]. Moreover, there is no solvents used in the processes, thus avoided the risk of secondary pollution. Compared with MEA absorption processes, no additional steam is required for solvent regeneration, thus low investment of modifications for installation retrofitting.

5. Challenges and prospects

Hybrid CO_2 capture process can be a potential alternative of exiting standalone processes in terms of efficiency. Nevertheless, the overall cost of the hybrid process has to be taken into consideration in terms of capital costs, operating costs and maintenance costs [131]. Most costs are very site-specific, and for a full-scale system these costs strongly depend on properties (e.g., CO_2 concentration, flow rate, temperature and pressure) of feed gas, the configuration of separation units, as well as the desired product quality [132]. In addition to the issue of overall cost, the specific challenges of each hybrid CO_2 capture process are summarized in Table 7. As one of the most common absorption based hybrid processes, CO_2 capture by membrane contactor has attracted much attention in the last decades. Wetting is a typical challenge of membrane contactor due to the rapid decline of its surface tension, especially for the low concentration organic solution [103]. Using hydrophobic membranes or hydrophobic modification, using composite membranes with dense skin layers, selecting liquids with high surface tension, increasing the compatibility between membranes and absorbents, or optimizing operation conditions would be effective approaches to prevent membrane wetting [49,103]. In addition, fouling and plugging problems of membrane should also be overcome (i.e. by SOx, water vapor and particle removal) before the large-scale

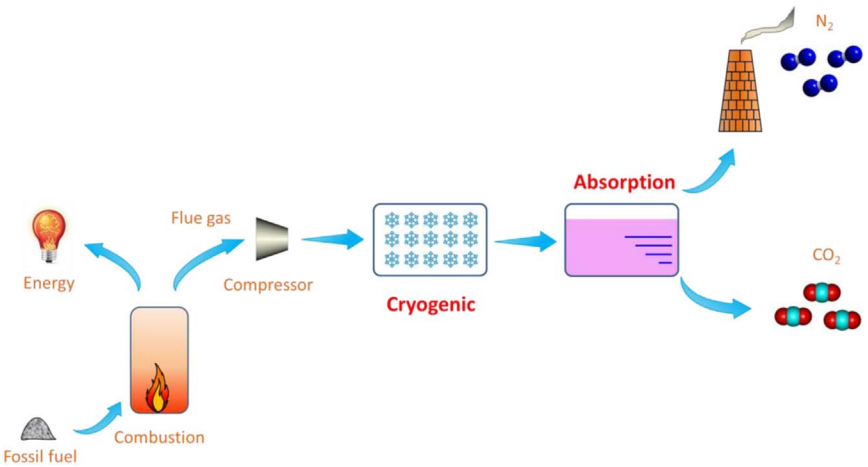


Fig. 16. Low temperature-absorption hybrid CO_2 capture process [97].

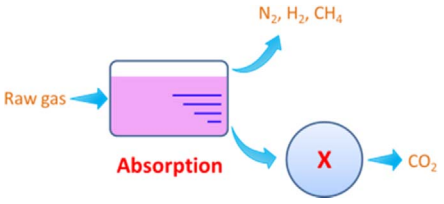
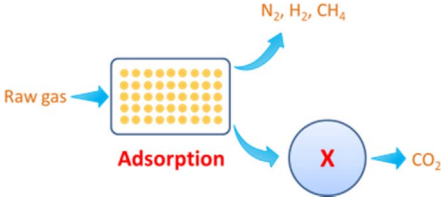
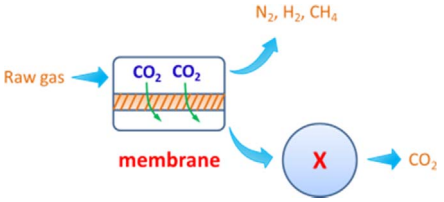
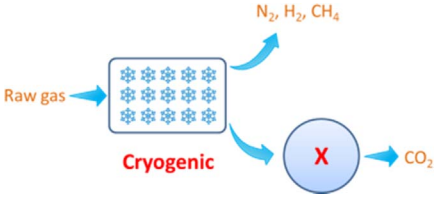
Table 5
Performance comparison of different low temperature based hybrid CO_2 capture processes.

Processes	Source of feed gas	CO_2 recovery (%)	CO_2 purity (%)	Energy consumption (GJ/ton CO_2)	References
Cryogenic-hydrate	Pre-combustion (40.3% CO_2, 2.8% CO, 55.1% H_2)	79	95–97	—	[89]
Low temperature-membrane-cryogenic	Post-combustion (15% CO_2, 85% N_2)	90	—	0.78–0.87 (electric energy)	[91]
Low temperature-absorption	Post-combustion (14.5% CO_2, 82.3% N_2, 3.2% O_2)	88.4	—	3.22 (thermal energy)	[102]

application [137]. For adsorption based hybrid processes, the CO_2 sorbents are usually mixed with reforming catalysts, and even in a membrane reactor. Instability of the existing sorbents in long-term operation due to the sintering phenomena at high temperatures would results in the decrease of efficiency. Extensive studies are highly needed to develop efficient hybrid catalyst–sorbent materials and evaluate their efficiency and stability under rigorous operation conditions and cyclic operation [110]. For membrane based hybrid processes, although CO_2 recovery can be enhanced by membrane-cryogenic process, the use of burner feed air as a membrane sweep gas could lead to dilution of oxygen in the furnace and thus reduced the overall power generation efficiency [88]. The optimization of configuration (e.g. adding air separation membrane to ensure O_2 concentration in burner) and membrane material is necessary to further reduce CO_2 capture cost. For cryogenic based hybrid processes, most of the related research is carried out in lab-scale or simulation. To reduce the energy penalty caused by cryogenic condition, the potential cold energy sources (e.g. liquid natural gas) are promising alternatives [128]. Meanwhile, further studies in pilot or large scale under real flue gas condition are important and would be well worth conducting.

To design a competitive hybrid CO_2 capture process, there are many kinds of combination ways, as shown in Fig. 18. Hereinto, the

Table 6
Advantages of different hybrid CO_2 capture processes.

Hybrid processes	Arrangements	Advantages	References
Absorption based 	Membrane contactor	• Larger interfacial area • Better device-modularity • More operational flexibility • Low investment costs and pumping power	[117–119]
	Absorption-membrane	• Decrease amine degradation of standalone absorption process • Higher lean-loading state (in series) • Mitigate fugitive amine emissions (in series) • Reduce investment due to small size (in parallel)	[41,120]
	Absorption-adsorption	• Decreasing the adsorption temperature • Promoted the ability of CO_2 capture under humid condition • Good stability and regeneration ability • Low regeneration temperatures	[52,121]
Adsorption based 	Adsorption-catalysis	• Change the normal equilibrium limits of shift reactions for producing high-purity hydrogen and increasing hydrocarbons conversion • A low-cost hydrogen production • Further purification treatment is usually not required	[122,123]
	Adsorption-catalysis-membrane	• Increase of CO conversion • Reduce CO_2 capture cost • Improve H_2 selectivity • Lower H_2 production cost	[60,124–126]
	Adsorption-cryogenic	• Liquid CO_2 product is easy to transportation and sequestration	[65]
	Adsorption-membrane	• Decrease of requirement on compressor • Reduction of energy consumption	[73]
	Adsorption-hydrate	• Improvement of hydrate formation kinetics • Significant increase of gas consumption • Increase of CO_2 selectivity	[127]
Membrane based 	Membrane-cryogenic	• High CO_2 recovery and purity • Capture cost (US$ 41–42 per ton of CO_2 avoided) is competitive with conventional MEA solvent technology	[88,128,129]
	Membrane-absorption	• High CO_2 recovery • High energy efficiency	[87]
Low temperature based 	Cryogenic-hydrate	• High CO_2 recovery • Low capture cost and energy demand	[89]
	Low temperature-membrane-cryogenic	• Large increases in CO_2/N_2 selectivity (two to four times compared to ambient temperature) • Long-term (8 months) stability	[91,115]
	Low temperature-absorption	• Prevent ammonia loss due to evaporation • Low theoretical heat of regeneration (0.67 GJ/ton CO_2 vs. 1.92 GJ/ton CO_2 for MEA)	[51,130]

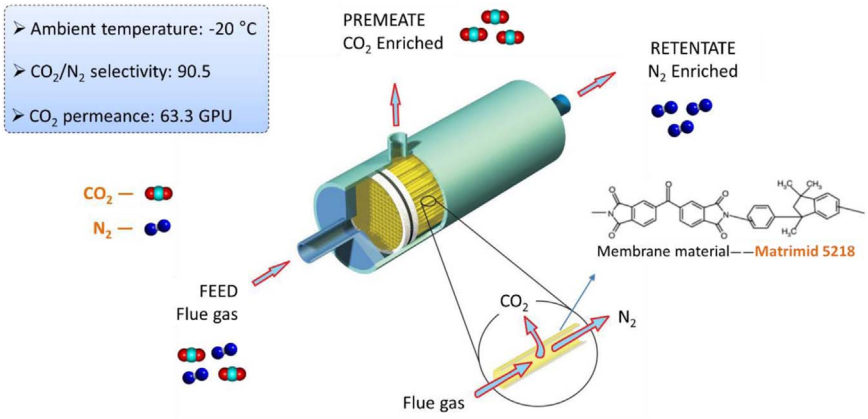
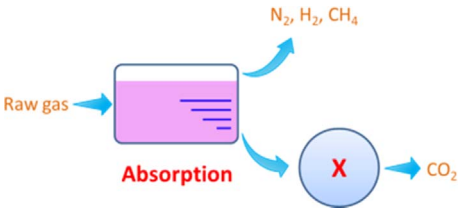
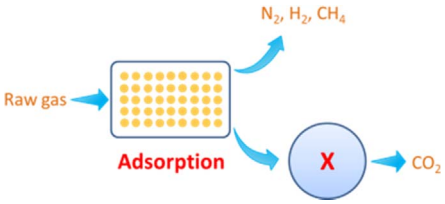
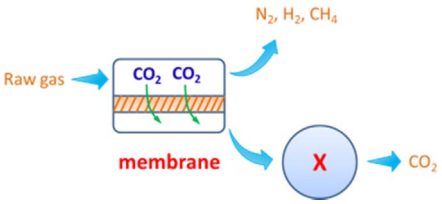
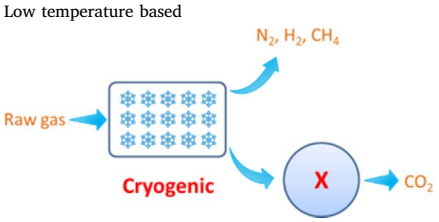


Fig. 17. Polyimide (Matrimid®5218) hollow fiber membrane module [83].

Table 7
Challenges of different hybrid CO_2 capture processes.

Hybrid processes	Arrangements	Challenges	References
Absorption based	Membrane contactor	• Wetting, fouling and plugging • Chemical stability • Thermal stability • Increased mass transfer resistance	[49,103]
	Absorption-membrane	• Capture cost is \$48/ton of CO_2, higher than the target (\$40/ton of CO_2) • O_2 dilution adversely effects membrane permeance	[45] [41]
	Absorption-adsorption	• Pore blockage and collapse of the pore structure • Reduced porosity and less accessibility	[134]
Adsorption based	Adsorption-catalysis	• Stringent requirement of sorbent (i.e. high reactivity, high decomposition temperature and high rates of reaction and regeneration) • Physical deterioration • Decay in reactivity through multiple CO_2 capture and release reactions • High desorption temperature leads to high energy consumption and adversely effect on catalyst stability	[108,135]
	Adsorption-catalysis-membrane	• Poison the membrane caused by CO • Integration of WGS reactor with membrane • Improvement of membrane selectivity for H_2 or CO_2 • Optimization of membranes for WGS reactor conditions	[60,126]
	Adsorption-cryogenic	• Moisture needs to be removed by pretreatment • High electric power requirement for low temperature unit	[65]
	Adsorption-membrane	• The cost of the heat exchanger is high	[73]
	Adsorption-hydrate	• Promoter is necessary to facilitate hydrate formation • CO_2 recovery is not high enough (< 80%)	[89]
Membrane based	Membrane-cryogenic	• Possibility of O_2 deficient in the burner • O_2 enrichment unit is necessary	[88]
	Membrane-absorption	• Ageing deterioration of membrane • Specific requirement on membrane materials	[136]
Low temperature based	Cryogenic-hydrate	• Laboratory scale test • Low CO_2 recovery • Ideal condition	[89]
	Low temperature-membrane-cryogenic	• Decrease of the membrane module productivity • Increase of capital cost • Humidity sensitivity	[100,115]
	Chilled-absorption	• High volatility • Toxicity and flammability	[97]

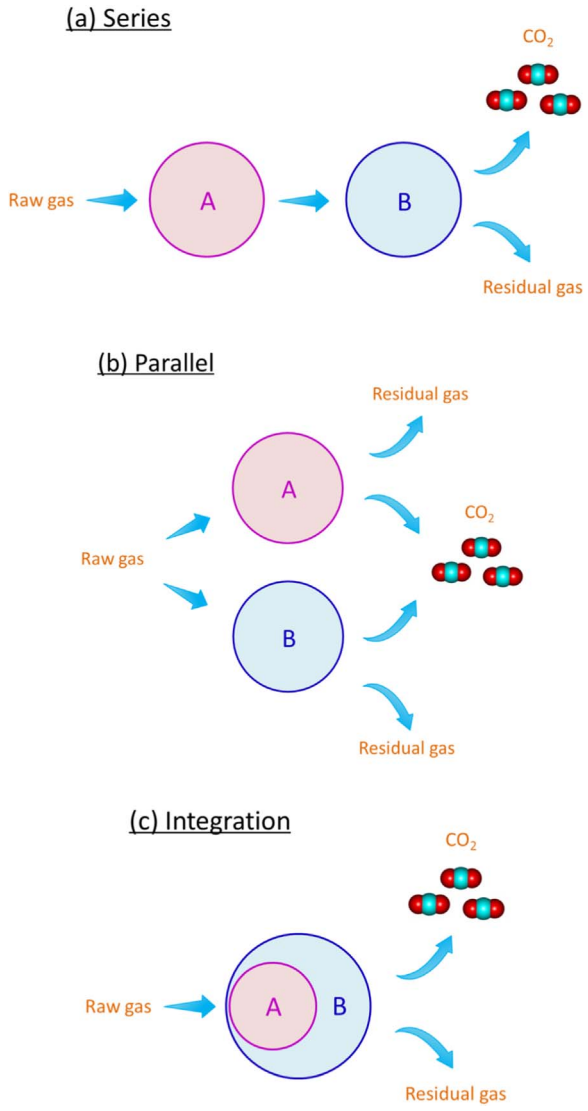


Fig. 18. Different ways of combining hybrid CO2 capture processes [41]. (a) Series arrangement, (b) parallel arrangement, (c) integration arrangement. A and B represent different standalone processes (i.e., absorption, adsorption, membrane, cryogenic, hydrate etc.).

arrangements of series and parallel are the most common routes [41]. Apart from the cascade/series or parallel, integration (e.g. cryogenic-membrane and cryogenic-absorption) may be a more effective mode. The choice of suitable arrangements in commercial applications should be further researched by taken a good use of each features. In addition, different from standalone processes, the hybrid processes have more rigorous requirement on the materials. Adsorption-catalysis hybrid processes need sorbents have both good sorption kinetics and heats of process [109]. Cryogenic-membrane hybrid process shows more stringent requirement on the properties of membrane, which can be used under cryogenic condition with high selectivity and permeability. The low CO_2 concentration and large volume of flue gas to be treated make membrane productivity become important, so higher CO_2 permeance is an attractive target for the future membrane based hybrid CO_2 processes [133]. Therefore, except hybrid process integration, advanced materials (solvents, sorbents, and membrane etc.) are also significant for efficient CO_2 capture, such as activated carbons, zeolite, alkanol amine, solid alkanol amine, carbonaceous, metal organic frameworks (MOFs), zeolitic imidazolate frameworks (ZIFs), covalent organic frameworks (COFs) and amine modified porous silica, etc. [138–140].

6. Conclusions

In this work, the status and development of hybrid CO_2 capture processes was reviewed. The existing hybrid CO_2 capture processes have been classified into four types (i.e. absorption based, adsorption based, membrane based and cryogenic based). The advantages and challenges of hybrid CO_2 capture processes are also summarized.

Compared to the standalone methods, hybrid processes show the superiority not only in CO_2 recovery and energy penalty, but also in the installation investment. For the typical post combustion strategy, the CO_2 capture cost of membrane contactor technology can be decreased to \$48/ton CO_2 with over 90% CO_2 recovery and 97% CO_2 purity at a membrane cost of \$30/m^2, which is closed to the target (\$40/ton CO_2) of DOE (U.S. Department of Energy) by 2025 [45]. Due to CO_2 initially concentrated by membrane units, substantial compression work can be avoided in membrane-cryogenic hybrid processes. Its CO_2 capture cost can be reduced to \$41–42/ton CO_2 (including FGD and SCR units) with 90% CO_2 recovery and 95% CO_2 purity [88].

The variety of combinations of hybrid processes presents great potential in various CO_2 emissions. In addition to series and parallel arrangement, integration of different technologies would be a more effective way of hybrid CO_2 capture processes. Until now, the integration of membrane into absorption process (i.e., membrane contactor), catalysis process (adsorption-catalysis-membrane) and cryogenic process (low-temperature-membrane-cryogenic) has made a significant progress.

Although increasing interest in the CO_2 capture by hybrid processes has been attracted in recent years and exciting results have been reported, amount of existing research is undertaken by simulation or lab-scale. Meanwhile, the concentration of CO_2 is limited to higher than 15%, and condition is also moderate than that in industrial emissions. In addition, the hybrid processes may result in the more stringent requirements on materials and equipment, such as cold resistance of membrane in the membrane-cryogenic system, and poison resistance of membrane in the adsorption-catalysis-membrane hybrid system etc. To overcome the issue of membrane wetting, a better understanding of the interactions between membranes and solutions, as well as the developments of both new membranes and novel green solvents, is required. Thus, there is still a long way ahead before this technique can be commercially applicable.

Acknowledgements

This work was supported by National Natural Science Funds of China (51506147), Natural Science Fund of Tianjin (17JCQNJC08500), and Special Fund of State Key Laboratory of Engines.

References

[1] International Energy Agency (IEA). CO_2 emissions from fuel combustion highlights. Website; 2014. ⟨http://www.iea.org/publications/freepublications/publication/⟩.
[2] Mondal MK, Balsora HK, Varshney P. Progress and trends in CO_2 capture/separation technologies: a review. Energy 2012;46:431–41.
[3] Guan G. Clean coal technologies in Japan: a review. Chin J Chem Eng 2017. http://dx.doi.org/10.1016/j.cjche.2016.12.008.
[4] Olajire AA. CO_2 capture and separation technologies for end-of-pipe applications - a review. Energy 2010;35:2610–28.
[5] Goto K, Yogo K, Higashii T. A review of efficiency penalty in a coal-fired power plant with post-combustion CO_2 capture. Appl Energy 2013;111:710–20.
[6] Merkel TC, Lin H, Wei X, Baker R. Power plant post-combustion carbon dioxide capture: an opportunity for membranes. J Membr Sci 2010;359:126–39.
[7] Oh SY, Binns M, Cho H, Kim JK. Energy minimization of MEA-based CO_2 capture process. Appl Energy 2016;169:353–62.
[8] Abu-Zahra MRM, Schneiders LHJ, Niederer JPM, Feron PHM, Versteeg GF. CO_2 capture from power plants Part I. A parametric study of the technical performance based on monoethanolamine. Int J Greenh Gas Control 2007;1:37–46.
[9] Ramezan M, Skone TJ, Nsakala N, Liljedahl GN. Carbon dioxide capture from existing coal-fired power plants 2017. [Final Report DOE/NETL-401/110907].
[10] Sipöcz N, Tobiesen FA. Review Natural gas combined cycle power plants with CO_2 capture – opportunities to reduce cost. Int J Greenh Gas Control 2012;7:98–106.

[11] Clausse M, Merel J, Meunier F. Numerical parametric study on CO_2 capture by indirect thermal swing adsorption. Int J Greenh Gas Control 2011;5(5):1206–13.
[12] Moullec YL, Kanniche M. Screening of flowsheet modifications for an efficient monoethanolamine (MEA) based post-combustion CO_2 capture. Int J Greenh Gas Control 2011;5:727–40.
[13] Ho MT, Allinson GW, Wiley DE. Factors affecting the cost of capture for australian lignite coal-fired power plants. Energy Procedia 2009;1:763–70.
[14] Siriwardhana M, Meng S, McNeill J. The impact of a carbon tax on the australian economy: results from a CGE model [Technical Report], Business, economics and public policy working papers, 2011 − 2. University of New England: Armidale, NSW, Australia; 2011.
[15] Raksajati A, Ho MT, Wiley DE. Reducing the cost of CO_2 capture from flue gases using aqueous chemical absorption. Ind Eng Chem Res 2013;52:16887–901.
[16] Rubin ES, Mantripragada H, Marks A, Versteeg P, Kitchin J. The outlook for improved carbon capture technology. Prog Energ Combust Sci 2012;38:630–71.
[17] Luis P, Gerven TV, Bruggen BVD. Recent developments in membrane-based technologies for CO_2 capture. Prog Energ Combust Sci 2012;38:419–48.
[18] Zhao L, Primabudia E, Stolten D. Investigation of a hybrid system for post-combustion capture. Energy Procedia 2014;63:1756–72.
[19] Bishnoi S, Rochelle GT. Absorption of carbon dioxide in aqueous piperazine/methyldiethanolamine. AIChE J 2002;48(12):2788–99.
[20] Aaron D, Tsouris C. Separation of CO_2 from flue gas: a review. Sep Sci Technol 2005;40:321–48.
[21] Sreedhar I, Nahar T, Venugopal A, Srinivas B. Carbon capture by absorption – path covered and ahead. Renew Sust Energ Rev 2017;76:1080–107.
[22] Samanta A, Zhao A, Shimizu GKH, Sarkar P, Gupta R. Post-combustion CO_2 capture using solid sorbents: a review. Ind Eng Chem Res 2012;51:1438–63.
[23] Ben-Mansour R, Habib MA, Bamidele OE, Basha M, Qasem NAA, Peedikakkal A, et al. Carbon capture by physical adsorption: materials, experimental investigations and numerical modeling and simulations – a review. Appl Energy 2016;161:225–55.
[24] Li B, Duan Y, Luebke D, Morreale B. Advances in CO_2 capture technology: a patent review. Appl Energy 2013;102:1439–47.
[25] Gao W, Zhou T, Gao Y, Louis B, O'Hare D, Wang Q. Molten salts-modified MgO-based adsorbents for intermediate-temperature CO_2 capture: a review. J Energy Chem 2017. http://dx.doi.org/10.1016/j.jechem.2017.06.005.
[26] Hussain A, Hägg MB. A feasibility study of CO_2 capture from flue gas by a facilitated transport membrane. J Membr Sci 2010;359:140–8.
[27] Pires JCM, Martins FG, Alvim-Ferraz MCM, Simões M. Recent developments on carbon capture and storage: an overview. Chem Eng Res Des 2011;89:1446–60.
[28] Scholes CA, Kentish SE, Stevens GW. The effect of condensable minor components on the gas separation performance of polymeric membranes for carbon dioxide capture. Energy Procedia 2009;1:311–7.
[29] Sreedhar I, Vaidhiswaran R, Kamani BM, Venugopal A. Process and engineering trends in membrane based carbon capture. Renew Sust Energy Rev 2017;68:659–84.
[30] Tuinier MJ, Annaland MVS, Kramer GJ, Kuipers JAM. Cryogenic CO_2 capture using dynamically operated packed beds. Chem Eng Sci 2010;65:114–9.
[31] Pan X, Clodic D, Toubassy J. CO_2 capture by antisublimation process and its technical economic analysis. Greenh Gas Sci Technol 2013;3:8–20.
[32] Monda MK, Balsora HK, Varshney P. Progress and trends in CO_2 capture/separation technologies: a review. Energy 2012;46:431–41.
[33] Song C, Liu Q, J N, Deng S, Zhao J, Li Y, et al. Reducing the energy consumption of membrane-cryogenic hybrid CO_2 capture by process optimization. Energy 2017;124:29–39.
[34] Park S, Lee S, Lee Y, Seo Y. CO_2 capture from simulated fuel gas mixtures using semiclathrate hydrates formed by quaternary ammonium salts. Environ Sci Technol 2013;47:7571–7.
[35] Yang M, Song Y, Jiang L, Zhu N, Liu Y, Zhao Y, et al. CO_2 hydrate formation and dissociation in cooled porous media: a potential technology for CO_2 capture and storage. Environ Sci Technol 2013;47:9739–46.
[36] Sun Q, Kang YT. Review on CO_2 hydrate formation/dissociation and its cold energy application. Renew Sust Energy Rev 2016;62:478–94.
[37] Ma ZW, Zhang P, Bao HS, Deng S. Review of fundamental properties of CO_2 hydrates and CO_2 capture and separation using hydration method. Renew Sust Energy Rev 2016;53:1273–302.
[38] Erans M, Manovic V, Anthony EJ. Calcium looping sorbents for CO_2 capture. Appl Energy 2016;180:722–42.
[39] Hossain MM, Lasa HID. Chemical-looping combustion (CLC) for inherent CO_2 separations—a review. Chem Eng Sci 2008;63:4433–51.
[40] Luo M, Yi Y, Wang S, Wang Z, Du M, Pan J, et al. Review of hydrogen production using chemical-looping technology. Renew Sust Energy Rev 2017. http://dx.doi.org/10.1016/j.rser.2017.07.007.
[41] Freeman B, Hao P, Baker R, Kniep J, Chen E, Ding J, et al. Hybrid membrane-absorption CO_2 capture process. Energy Procedia 2014;63:605–13.
[42] Scholz M, Frank B, Stockmeier F, Falß S, Wessling M. Techno-economic analysis of hybrid processes for biogas upgrading. Ind Eng Chem Res 2013;52:16929–38.
[43] Zhao L, Riensche E, Menzer R, Blum L, Stolten D. A parametric study of CO_2/N_2 gas separation membrane processes for post-combustion capture. J Membr Sci 2008;325:284–94.
[44] Song C, Kitamura Y, Li S, Lu J. Deposition CO_2 capture process using a free piston stirling cooler. Ind Eng Chem Res 2013;52:14936–43.
[45] Li S, Zhou J, Pyrzynski A, Makkuni A, Meyer H, Ding Y, et al. Hybrid membrane/absorption process for post-combustion CO_2 capture [Final Technical Report]. 2014.
[46] Gabelman A, Hwang ST. Hollow fiber membrane contactors. J Membr Sci 1999;159:61–106.
[47] Feron PHM, Jansen AE, Klaassen R. Membrane technology in carbon dioxide removal. Energ Convers Manag 1992;33:421–8.
[48] Cui Z, deMontigny D. Experimental study of carbon dioxide absorption into aqueous ammonia with a hollow fiber membrane contactor. J Membr Sci 2017;540:297–306.
[49] Zhao S, Feron PHM, Deng L, Favre E, Chabanon E, Yan S, et al. Status and progress of membrane contactors in post-combustion carbon capture: a state-of-the-art review of new developments. J Membr Sci 2016;511:180–206.
[50] Rochelle G, Chen E, Dombrowski K, Sexton A, Lani B. Pilot plant testing of piperazine (PZ) with high temperature regeneration. Presented at NETL's CO_2 capture technology meeting, Pittsburgh, United States; July 31 2014.
[51] National Energy Technology Laboratory. Carbon dioxide capture from existing coal-fired power plants [Final Report] 2007. (DOE/NETL-401/110907).
[52] Brilman DWF, Veneman R. Capturing atmospheric CO_2 using supported amine sorbents. Energy Procedia 2013;37:6070–8.
[53] Ahmad NA, Mohd Noh AN, Leo CP, Ahmad AL. CO_2 removal using membrane gas absorption with PVDF membrane incorporated with POSS and SAPO-34 zeolite. Chem Eng Res Des 2017;118:238–47.
[54] Moullec YL, Neveux T, Makhloufi K, Roizard D, Kanniche M, Favre E. Development of a CO_2 capture process based on ammonia solvent and a dedicated composite hollow fibre membrane contactor. Energy Procedia 2014;63:651–8.
[55] Ding J, Lin YT, Rochelle GT. Optimization of stripping concentrated piperazine over a wide range of rich loading. Energy Procedia 2014;63:1842–53.
[56] Breault RW, Spenik JL, Shadle LJ, Hoffman JS, Gray ML, Panday R, et al. Carbon capture test unit design and development using amine-based solid sorbent. Chem Eng Res Des 2016;112:251–62.
[57] Van Selow ER, Cobden PD, Wright A, Van den Brink RW, Jansen D. Improved sorbent for the sorption-enhanced water-gas shift process. Energy Procedia 2011;4:1090–5.
[58] Ochoafernández E, Haugen G, Zhao T, Rønning M, Aartun I, Børresen B, et al. Process design simulation of H_2 production by sorption enhanced steam methane reforming: evaluation of potential CO_2 acceptors. Green Chem 2007;9:654–62.
[59] Maroño M, Torreiro Y, Cillero D, Sánchez JM. Experimental studies of CO_2 capture by a hybrid catalyst/adsorbent system applicable to IGCC processes. Appl Therm Eng 2015;74:28–35.
[60] Soria MA, Tosti S, Mendes A, Madeira LM. Enhancing the low temperature water–gas shift reaction through a hybrid sorption-enhanced membrane reactor for high-purity hydrogen production. Fuel 2015;159:854–63.
[61] Maroño M, Barreiro MM, Torreiro Y, Sánchez JM. Performance of a hybrid system sorbent–catalyst–membrane for CO_2 capture and H_2 production under pre-combustion operating conditions. Catal Today 2014;236:77–85.
[62] Cornaglia L, Múnera J, Lombardo E. Recent advances in catalysts, palladium alloys and high temperature WGS membrane reactors: a review. Int J Hydrog Energy 2015;40:3423–37.
[63] Brunetti A, Barbieri G, Drioli E, Lee KH, Sea B, Lee DW. WGS reaction in a membrane reactor using a porous stainless steel supported silica membrane. Chem Eng Process 2007;46:119–26.
[64] Peters TA, Stange M, Klette H, Bredesen R. High pressure performance of thin Pd–23% Ag/stainless steel composite membranes in water gas shift gas mixtures; influence of dilution, mass transfer and surface effects on the hydrogen flux. J Membr Sci 2008;316:119–27.
[65] Fong JCLY, Anderson CJ, Xiao G, Webley PA, Hoadley AFA. Multi-objective optimisation of a hybrid vacuum swing adsorption and low-temperature post-combustion CO_2 capture. J Clean Prod 2016;111:193–203.
[66] Budzianowski WM, Postawa K. Renewable energy from biogas with reduced carbon dioxide footprint: implications of applying different plant configurations and operating pressures. Renew Sust Energy Rev 2016. http://dx.doi.org/10.1016/j.rser.2016.05.076i.
[67] Tippayawong N, Thanompongchart P. Biogas quality upgrade by simultaneous removal of CO_2 and H_2S in a packed column reactor. Energy 2010;35:4531–5.
[68] Deng L, Hägg MB. Techno-economic evaluation of biogas upgrading process using CO_2 facilitated transport membrane. Int J Greenh Gas Control 2010;4:638–46.
[69] Budzianowski WM. Sustainable biogas energy in Poland: prospects and challenges. Renew Sust Energy Rev 2012;16:342–9.
[70] Budzianowski WM, Wylock CE, Marciniak PA. Power requirements of biogas upgrading by water scrubbing and biomethane compression: comparative analysis of various plant configurations. Energy Convers Manag 2017;141:2–19.
[71] Tuinier MJ, Annaland MVS. Biogas purification using cryogenic packed-bed technology. Ind Eng Chem Res 2012;51:5552–8.
[72] Scholz M, Melin T, Wessling M. Transforming biogas into biomethane using membrane technology. Renew Sust Energ Rev 2013;17:199–212.
[73] Shao P, Dal-Cin M, Kumar A, Li H, Singh DP. Design and economics of a hybrid membrane–temperature swing adsorption process for upgrading biogas. J Membr Sci 2012;413–414:17–28.
[74] Englezos P. Clathrate hydrates. Ind Eng Chem Res 1993;32:1251–74.
[75] Sloan ED, Koh CA. Clathrate hydrates of natural gases. Third ed. Baca Raton, FL: Taylor & Francis, CRC Press; 2008.
[76] Sun D, Englezos P. Storage of CO_2 in a partially water saturated porous medium at gas hydrate formation conditions. Int J Greenh Gas Control 2014;25:1–8.
[77] Park S, Lee S, Lee Y, Lee Y, Seo Y. Hydrate-based pre-combustion capture of carbon dioxide in the presence of a thermodynamic promoter and porous silica gels. Int J Greenh Gas Control 2013;14:193–9.
[78] Yang MJ, Song YC, Jiang LL, Liu Y, Li YH. CO_2 hydrate formation characteristics in a water/brine-saturated silica gel. Ind Eng Chem Res 2014;53(26):10753–61.
[79] Yan L, Chen G, Pang W, Liu J. Experimental and modeling study on hydrate

formation in wet activated carbon. J Phys Chem B 2005;109:6025–30.
[80] Siangsai A, Rangsunvigit P, Kitiyanan B, Kulprathipanja S, Linga P. Investigation on the roles of activated carbon particle sizes on methane hydrate formation and dissociation. Chem Eng Sci 2015;126:383–9.
[81] Li Z, Zhong DL, Lu YY, Wang JL, Qing SL, Yan J. Enhanced separation of carbon dioxide from a CO_2 + CH_4 gas mixture using a hybrid adsorption-hydrate formation process in the presence of coal particles. J Nat Gas Sci Eng 2016. http://dx.doi.org/10.1016/j.jngse.2016.03.081.
[82] Boon J, Spallina V, Delft YV, Annaland MVS. Comparison of the efficiency of carbon dioxide capture by sorption-enhanced water–gas shift and palladium-based membranes for power and hydrogen production. Int J Greenh Gas Control 2016;50:121–34.
[83] Zhong DL, Wang JL, Lu YY, Li Z, Yan J. Precombustion CO_2 capture using a hybrid process of adsorption and gas hydrate formation. Energy 2016;102:621–9.
[84] Anantharaman R, Berstad D, Roussanaly S. Techno-economic performance of a hybrid membrane –liquefaction process for post-combustion CO_2 capture. Energy Procedia 2014;61:1244–7.
[85] Burdyny T, Struchtrup H. Hybrid membrane/cryogenic separation of oxygen from air for use in the oxy-fuel process. Energy 2010;35:1884–97.
[86] Belaissaoui B, Moullec YL, Willson D, Favre E. Hybrid membrane cryogenic process for post-combustion CO_2 capture. J Membr Sci 2012;415–416:424–34.
[87] Kundu PK, Chakma A, Feng X. Effectiveness of membranes and hybrid membrane processes in comparison with absorption using amines for post-combustion CO_2 capture. Int J Greenh Gas Control 2014;28:248–56.
[88] Scholes CA, Ho MT, Wiley DE, Stevens GW, Kentish SE. Cost competitive membrane—cryogenic post-combustion carbon capture. Int J Greenh Gas Control 2013;17:341–8.
[89] Surovtseva D, Amin R, Barifcani A. Design and operation of pilot plant for CO_2 capture from IGCC flue gases by combined cryogenic and hydrate method. Chem Eng Res Des 2011;89:1752–7.
[90] Sreenivasulu B, Gayatri DV, Sreedhar I, Raghavan KV. A journey into the process and engineering aspects of carbon capture technologies. Renew Sust Energ Rev 2015;41:1324–50.
[91] Hasse D, Kulkarni S, Sanders E, Corson E, Tranier J. CO_2 capture by sub-ambient membrane operation. Energy Procedia 2013;37:993–1003.
[92] Kulkarni SS. CO_2 capture by sub-ambient membrane operation. In: 2012 NETL CO_2 capture technology meeting; July 9 – 12, 2012. NETL Award # DE-FE0004278.
[93] Wang M, Lawal A, Stephenson P, Sidders J, Ramshaw C. Post-combustion CO_2 capture with chemical absorption: a state-of-the-art review. Chem Eng Res Des 2011;89:1609–24.
[94] IEAGHG. Improvements in power generation with post-combustion capture of CO_2, PH4/33. UK: IEA Greenhouse Gas R & D Programme; 2004.
[95] Pfaff I, Oexmann J, Kather A. Optimised integration of post-combustion CO_2 capture process in greenfield power plants. Energy 2010;35(10):4030–41.
[96] Qi G, Wang S, Yu H, Wardhaugh L, Feron P, Chen C. Development of a rate-based model for CO_2 absorption using aqueous NH3 in a packed column. Int J Greenh Gas Control 2013;17:450–61.
[97] Hanak DP, Biliyok C, Manovic V. Rate-based model development, validation and analysis of chilled ammonia process as an alternative CO_2 capture technology for coal-fired power plants. Int J Greenh Gas Control 2015;34:52–62.
[98] Zhao B, Su Y, Tao W, Li L, Peng Y. Post-combustion CO_2 capture by aqueous ammonia: a state-of-the-art review. Int J Greenh Gas Control 2012;9:355–71.
[99] Strube R, Manfrida G. CO_2 capture in coal-fired power plants – impact on plant performance. Int J Greenh Gas Control 2011;5(4):710–26.
[100] Clodic D, Younes M. A new method for CO_2 capture: frosting CO_2 at atmospheric pressure. In: Proceedings of the sixth international conference on Greenhouse Gas Control Technologies, GHGT-6, Kyoto, Japan, 1–4 Oct 2002; p. 155–60 [CD ROM].
[101] Tuinier MJ, van Sint Annaland M, Kramer GJ, Kuipers JAM. Cryogenic CO_2 capture using dynamically operated packed beds. Chem Eng Sci 2010;65:114–9.
[102] Valenti G, Bonalumi D, Macchi E. A parametric investigation of the Chilled Ammonia Process from energy and economic perspectives. Fuel 2012;101:74–83.
[103] Li JL, Chen BH. Review of CO_2 absorption using chemical solvents in hollow fiber membrane contactors. Sep Purif Technol 2005;41:109–22.
[104] deMontigny D, Tontiwachwuthikul P, Chakma A. Using polypropylene and polytetrafluoroethylene membranes in a membrane contactor for CO_2 absorption. J Membr Sci 2006;277:99–107.
[105] Khaisri S, deMontigny D, Tontiwachwuthikul P, Jiraratananon R. Comparing membrane resistance and absorption performance of three different membranes in a gas absorption membrane contactor. Sep Purif Technol 2009;65:290–7.
[106] Li S, Rocha DJ, Zhou SJ, Meyer HS, Bikson B, Ding Y. Post-combustion CO_2 capture using super-hydrophobic, polyether ether ketone, hollow fiber membrane contactors. J Membr Sci 2013;430:79–86.
[107] Gottschlich DE, Roberts DL. Energy minimization of separation processes using conventional/membrane hybrid systems. Menlo Park: U.S. Department of Energy; 1990.
[108] Silva JM, Soria MA, Madeira LM. Challenges and strategies for optimization of glycerol steam reforming process. Renew Sust Energ Rev 2015;42:1187–213.
[109] Dou B, Wang C, Song Y, Chen H, Jiang B, Yang M, et al. Solid sorbents for in-situ CO_2 removal during sorption-enhanced steam reforming process: a review. Renew Sust Energ Rev 2016;53:536–46.
[110] Yancheshmeh MS, Radfarnia HR, Iliuta MC. High temperature CO_2 sorbents and their application for hydrogen production by sorption enhanced steam reforming process. Chem Eng J 2016;283:420–44.
[111] Bhide B, Voskericyan A, Stern S. Hybrid processes for the removal of acid gases from natural gas. J Membr Sci 1998;140(1):27–49.
[112] Baker R, Lokhandwala K. Natural gas processing with membranes: an overview. Ind Eng Chem Res 2008;47(7):2109–21.
[113] Liu L, Sanders ES, Johnson JR, Karvan O, Kulkarni S, Hasse DJ, et al. Influence of membrane skin morphology on CO_2/N_2 separation at subambient temperatures. J Membr Sci 2013;446:433–9.
[114] Liu L, Sanders ES, Kulkarni SS, Hasse DJ, Koros WJ. Sub-ambient temperature flue gas carbon dioxide capture via Matrimids hollow fiber membranes. J Membr Sci 2014;465:49–55.
[115] Hasse D, Ma J, Kulkarni S, Terrien P, Tranier JP, Sanders E, et al. CO_2 capture by cold membrane operation. Energy Procedia 2014;63:186–93.
[116] Berstad D, Anantharaman R, Neksa P. Low-temperature CO_2 capture technologies-applications and potential. Int J Refrig 2013;36:1403–16.
[117] Li JL, Chen BH. Review of CO_2 absorption using chemical solvents in hollow fiber membrane contactors. Sep Purif Technol 2005;41:109–22.
[118] Mansourizadeh A, Ismail AF. Hollow fiber gas–liquid membrane contactors for acid gas capture: a review. J Hazard Mater 2009;171:38–53.
[119] Ansaloni L, Rennemo R, Knuutila HK, Deng L. Development of membrane contactors using volatile amine-based absorbents for CO_2 capture: amine permeation through the membrane. J Membr Sci 2017;537:272–82.
[120] Sanna A, Vega F, Navarrete B, Maroto-Valer MM. Accelerated MEA degradation study in hybrid CO_2 capture systems. Energy Procedia 2014;63:745–9.
[121] Liu X, Gao F, Xu J, Zhou L, Liu H, Hu J. Zeolite@Mesoporous silica-supported-amine hybrids for the capture of CO_2 in the presence of water. Microporous Mesoporous Mater 2016;222:113–9.
[122] Essaki K, Muramatsu T, Kato M. Effect of equilibrium shift by using lithium silicate pellets in methane steam reforming. Int J Hydrog Energy 2008;33:4555–9.
[123] He L, Parra JMS, Blekkan EA, Chen D. Towards efficient hydrogen production from glycerol by sorption enhanced steam reforming. Energy Environ Sci 2010;3:1046–56.
[124] Dou BL, Song YC, Wang C, Chen HS, Xu YJ. Hydrogen production from catalytic steam reforming of biodiesel byproduct glycerol: issues and challenges. Renew Sustain Energy Rev 2014;30:950–60.
[125] Barelli L, Bidini G, Gallorini F, Servili S. Hydrogen production through sorption-enhanced steam methane reforming and membrane technology: a review. Energy 2008;33:554–70.
[126] National Energy Technology Laboratory. DOE/NETL carbon dioxide capture and storage RD & D roadmap. Washington, DC: US Department of Energy; 2010.
[127] Babu P, Kumar R, Linga P. Medium pressure hydrate based gas separation (HBGS) process for pre-combustion capture of carbon dioxide employing a novel fixed bed reactor. Int J Greenh Gas Control 2013;17:206–14.
[128] Song C, Liu Q, Ji N, Deng S, Zhao J, Kitamura Y. Advanced cryogenic CO_2 capture process based on Stirling coolers by heat integration. Appl Therm Eng 2017;114:887–95.
[129] Shafiee A, Nomvar M, Liu Z, Abbas A. Automated process synthesis for optimal flowsheet design of a hybrid membrane cryogenic carbon capture process. J Clean Prod 2017;150:309–23.
[130] Bak CU, Asif M, Kim WS. Experimental study on CO_2 capture by chilled ammonia process. Chem Eng J 2015;265:1–8.
[131] Hai FI, Yamamoto K, Fukushi K. Hybrid treatment systems for dye wastewater. Crit Rev Environ Sci Technol 2007;37(4):315–77.
[132] Tee PF, Abdullah MO, Tan IAW, Rashid NKA, Amin MAM, Hipolito CN, et al. Review on hybrid energy systems for waste water treatment and bio-energy production. Renew Sust Energ Rev 2016;54:235–46.
[133] Liu L, Qiu W, Sanders ES, Ma C, Koros WJ. Post-combustion carbon dioxide capture via 6FDA/BPDA-DAM hollow fiber membranes at sub-ambient temperatures. J Membr Sci 2016;510:447–54.
[134] Rezaei F, Sakwa-Novak MA, Bali S, Duncanson DM, Jones CW. Shaping amine-based solid CO_2 adsorbents: effects of pelletization pressure on the physical and chemical properties. Microporous Mesoporous Mater 2015;204:34–42.
[135] Florin NH, Harris AT. Review: enhanced hydrogen production from biomass with in situ carbon dioxide capture using calcium oxide sorbents. Chem Eng Sci 2008;63:287–316.
[136] Li X, Remias JE, Neathery JK, Liu K. NF/RO faujasite zeolite membrane-ammonia absorption solvent hybrid system for potential post-combustion CO_2 capture application. J Membr Sci 2011;366:220–8.
[137] Zhang L, Qu R, Sha Y, Wang X, Yang L. Membrane gas absorption for CO_2 capture from flue gas containing fine particles and gaseous contaminants. Int J Greenh Gas Control 2015;33:10–7.
[138] Olajire AA. Recent advances in the synthesis of covalent organic frameworks for CO_2 capture. J CO_2 Util 2017;17:137–61.
[139] Zhou K, Chaemchuen S, Verpoort F. Alternative materials in technologies for Biogas upgrading via CO_2 capture. Renew Sust Energ Rev 2017;79:1414–41.
[140] Wang J, Huang L, Yang R, Zhang Z, Wu J, Gao Y, et al. Recent advances in solid sorbents for CO_2 capture and new development trends. Energy Environ Sci 2014;7:3478–518.